GRAPHENE FLAGSHIP

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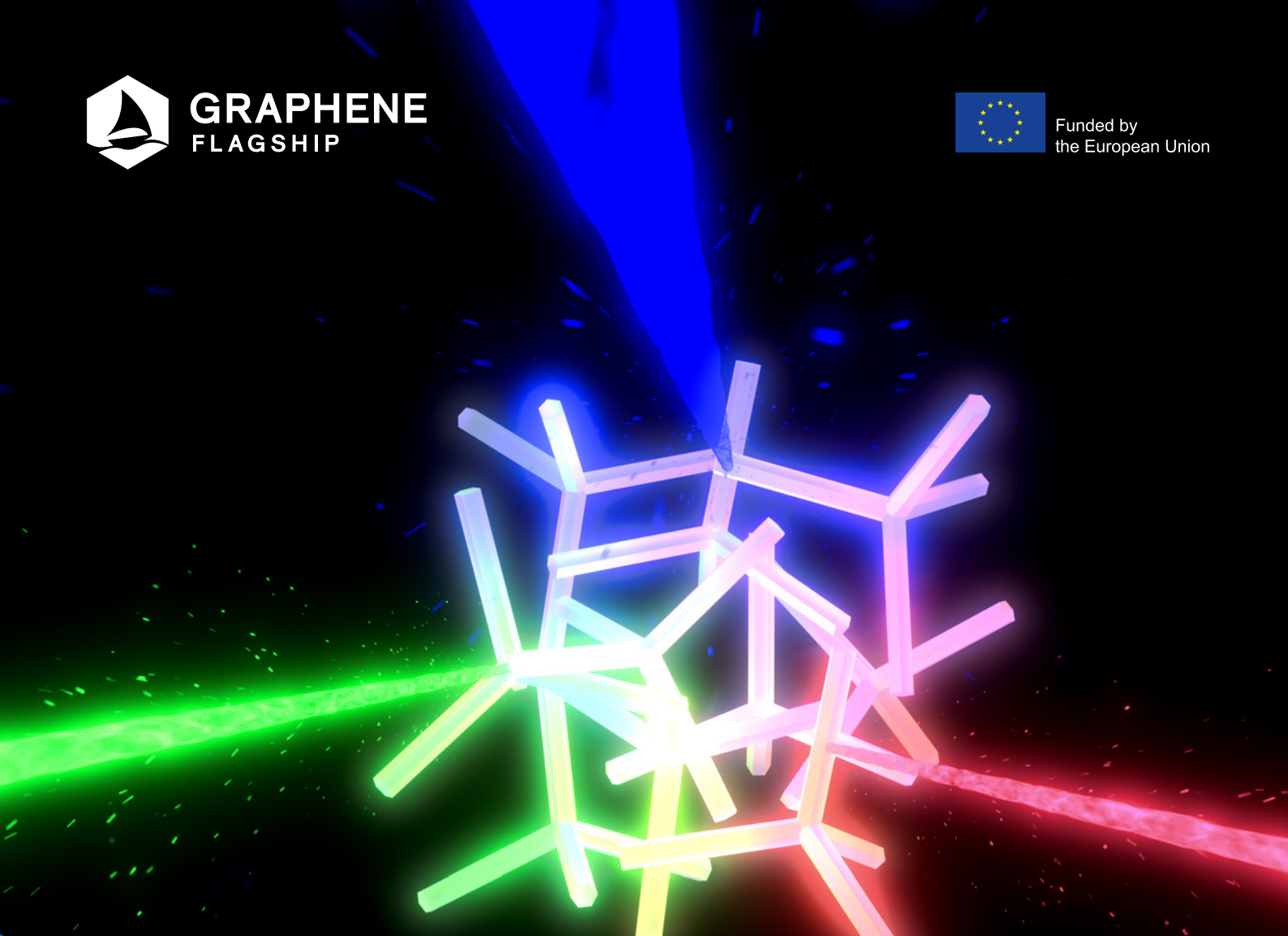

Graphene Flagship Annual Report 2019

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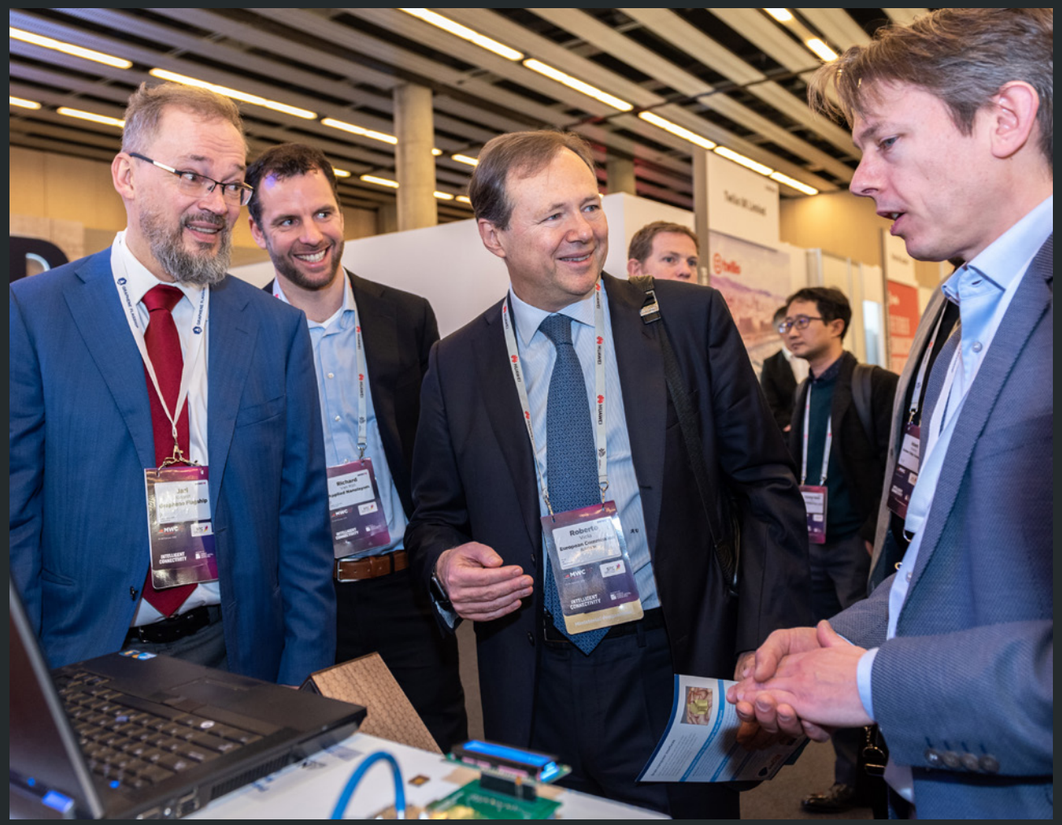
Front cover
Graphical representation of an aero-BN diffuser exposed to three laser beams, created by the Graphene Flagship's Functional Foams and Coatings Work Package. To read more, please see page 24. Image credit: Fabian Schütt from Kiel University



Above
Graphene Flagship Director Jari Kinaret shows European Commission Director General of DG CONNECT, Roberto Viola, around the Graphene Pavilion at Mobile World Congress 2019. Image credit: Alexandra Csuport

From the Director

Over the past year, the Graphene Flagship community has produced numerous scientific and technological breakthroughs which are described in more detail in the topical sections of this annual report. I would, however, like to highlight a few of them as they are representative of our overall progress and impact.

Working on biomedical applications, ICN2, the University of Sorbonne and other institutions have made great progress towards graphene-based retinal implants and have received substantial additional funding from Spanish organisations for their continued work.

In the Functional Foams and Coatings Work Package, Tecnalia has developed capacitive deionisation techniques to remove 60% of the salt in sea water, paving the way to new irrigation systems in challenging environments, and demonstrating our commitment to sustainable development.

In the area of optoelectronics, Emberion Oy, a spin-off created within the Graphene Flagship, recently announced the third product in their series of graphene-based wide-band photodetectors – a VGA-standard video camera operating at wavelengths from infrared to visible light.

Finally, I would like to mention two activities, both of which are crucial to bringing graphene and layered materials to industrial maturity: the Validation Service, led by Alexander Tzalenchuk at the National Physical Laboratory, and the Experimental Pilot Line, which we started planning in 2019. The Pilot Line, which is expected to start its operation in 2020, aims at overcoming the hurdle between the lab and the fab, and bring the manufacturing of graphene-based electronics, photonics and sensors to industrially relevant levels.

OUR VISION

In 2020 we will enter Core 3, the next phase of the project, which runs for three years starting 1 April 2020. This phase represents a clear progression towards higher technology readiness levels, with 30% of our budget assigned to market-motivated Spearhead Projects. This shift is also evident in the composition of the Core 3 consortium: about one quarter of the Core 3 partners are new to the Graphene Flagship, and the proportion of industrial partners has grown to nearly 50%.

> The Graphene Flagship has proven very successful in taking fundamental research to applications.”

WORKING TOWARDS A SUSTAINABLE FUTURE

Sustainable development has been a major motivator for the Graphene Flagship since the very beginning: much of our work focuses on energy efficiency, the replacement of rare materials by common ones, and ensuring the environmental compatibility of our actions. In the coming years, we will make this focus even more clearly visible and see to it that both the goals of our research and innovation, as well as the ways in which they are pursued, are on a firm, sustainable footing.

PAVING THE WAY FOR INDUSTRY

The Graphene Flagship has proven very successful in taking fundamental research to applications, doubling the usual pace of innovation and achieving results in just six years. We have demonstrated how to build a European industrial ecosystem, created several spin-off companies and helped them cross the valley of death, so that they are now growing and releasing commercial products to the market. I am convinced that this trend will continue in the next phase of the project and we will continue to deliver on the promises we have made. The Graphene Flagship is a major European force propagating a revitalising technology shift in this era of increasing global competition.

Jari Kinaret
Graphene Flagship Director

European Research, Innovation and Collaboration

Since its launch in 2013, the Graphene Flagship has provided the foundation for innovative new companies, new graphene-enabled products and high-technology readiness level research and technologies. We achieve this by collaborating closely with academia, small and medium enterprises and large corporations across Europe. The second phase of our project is coming to an end, and at present, the Graphene Flagship consortium includes nearly 150 organisations in 21 EU member states and associated countries. Through the Graphene Flagship, Europe has established itself as the global leader for technologies based on graphene and layered materials – and thanks to our efforts, Europe is poised to continue leading this technological revolution for the foreseeable future.

OUR VISION

Moving forward into the next phase of the project, the Graphene Flagship will continue to support fundamental research, expanding to study the myriad of layered materials that follow in the footsteps of graphene and are still at the early stages of technological development. But our main emphasis, during this new phase, will be to foster more mature applied research and push graphene-enabled technologies towards commercialisation. Roughly one third of our project's funding will be invested to support industry-led Spearhead Projects with well-defined objectives, motivated by market opportunities. Focusing our work on applications will further increase the maturity of graphene in areas at the core of European industry, such as the automotive, aerospace, energy, electronics and health industries.

Technology Readiness Level[1]

1 Basic principles observed
2 Technology concept formulated
3 Experimental proof-of-concept created
4 Validated in the lab
5 Validated in an industrially relevant environment
6 Demonstrated in an industrially relevant environment
7 Prototype demonstrated in an operational environment
8 System complete and qualified
9 Competitive manufacturing

1. The European Commission's definition of technology readiness levels, Horizon 2020 Work Programme (2014): bit.ly/grapheneTRL

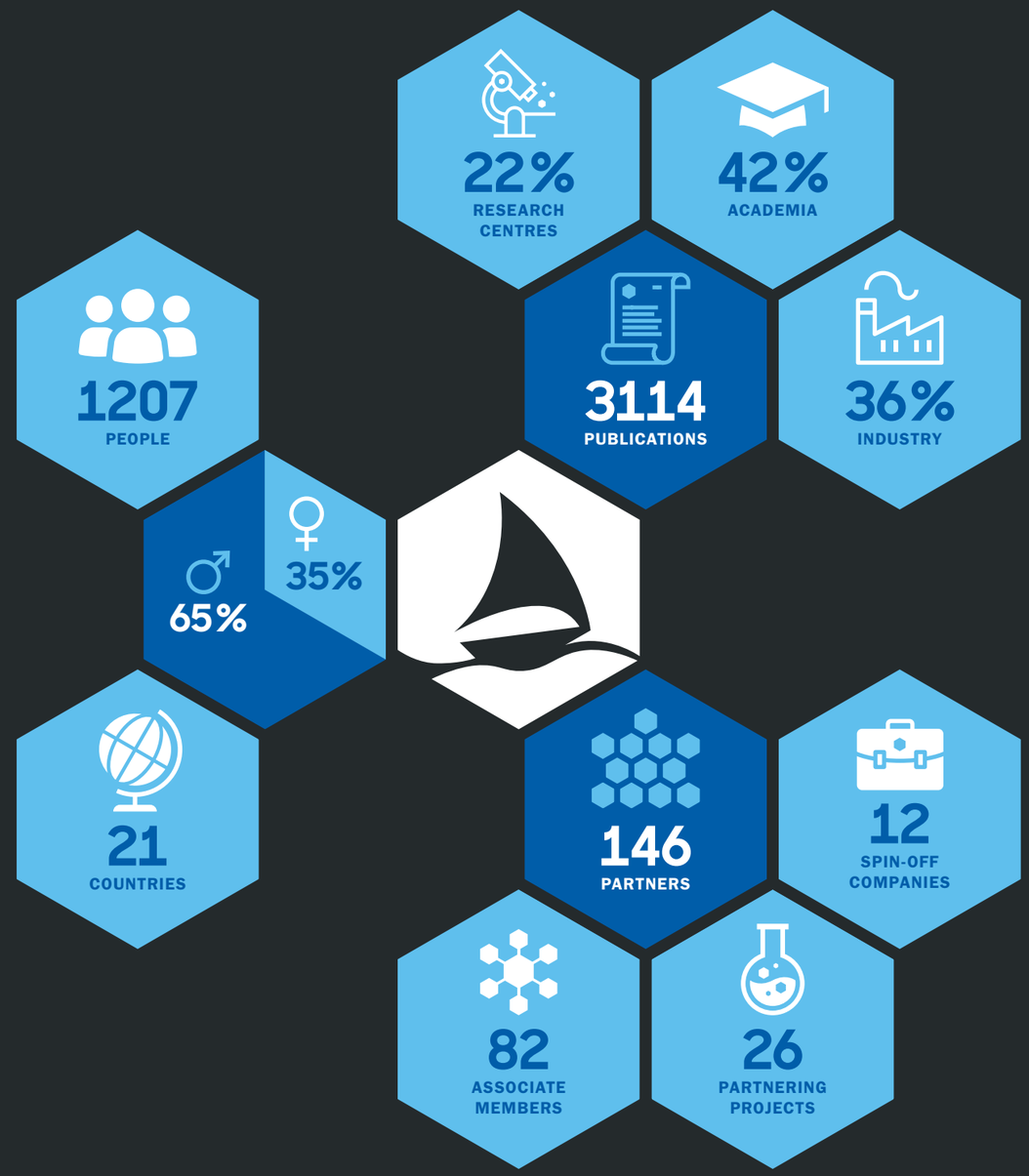
Perspectives

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 five years' time, I would be very happy to see sustainable, autonomous wearable devices relying on the Graphene Flagship's developments for their electronic components, power source and the sensors integrated within."
Maria Smolander
VTT

Airbus introduced a new Spearhead Project last year to utilise graphene as a key material for ice protection systems. With graphene, we can reduce the complexity of these systems and reduce energy use, fuel consumption and CO_2 and NO_x emissions – helping us work towards a more environmentally friendly future of aviation."
Elmar Bonaccurso
Airbus

I'm a PhD student, and since I've been a part of the Graphene Flagship I have had the opportunity to work on two space campaigns. I'm very excited for future graphene space applications. In the near future, I expect to be able to use graphene to print in space."
Vanja Miscovic
Microgravity Research Center



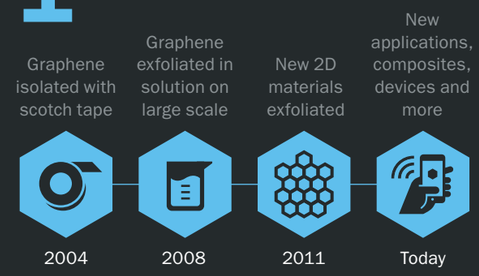
GRAPHENE FLAGSHIP ANNUAL REPORT 2019

Top
Women in Graphene, organised by the Management Work Package, supports gender diversity in science by providing a support network for women working in the Graphene Flagship.
Image credit: Vesa Laitinen

Bottom
The Open Forum at Graphene Week presents a variety of perspectives on the Graphene Flagship's progress.
Image credit: Vesa Laitinen

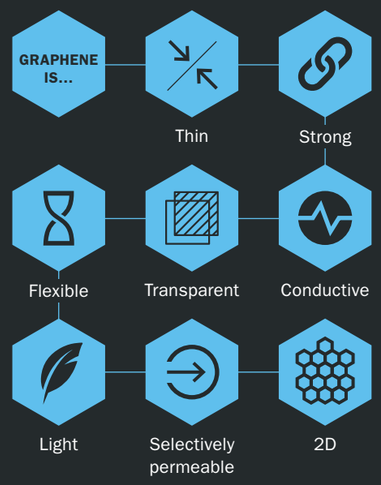
What is Graphene?

1 History



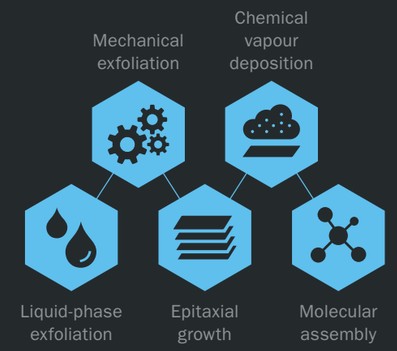
2 Properties

Graphene has a unique combination of properties that give it great potential in research and industry.



3 Production

Graphene can be produced through various different methods, each with its own perks.



4 Applications

Many areas of research and industry use graphene to enhance their products and develop new concepts.

Management

Work Package Leader
Jari Kinaret, Graphene Flagship Director

Head of Administration
Macarena Muñoz-Ruiz, Chalmers University of Technology, Sweden

The Graphene Flagship's legal, ethical, financial and administrative management

The Graphene Flagship's Management Work Package coordinates the Graphene Flagship and makes sure that it operates in an efficient manner. We monitor the development of the project, make sure that it stays on course and keep track of its outputs. We host the meetings of the governing bodies, manage connections with stakeholders and provide service functions for our consortium. We are in direct contact with the Partnering Division and in constant dialogue with the National Funding Agencies involved in FLAG-ERA.

2019: A YEAR IN REVIEW

Over the past year we coordinated the preparations for the Core 3 and Experimental Pilot Line proposals, projects that will start running in 2020; jointly, these projects result in 170 million euros funding for the Graphene Flagship consortium. We also launched seven calls for Spearhead Projects and other actions to bring new competence to the Core 3 project. As a result, Core 3 will have 11 Spearhead Projects and over 30 new partners.

We closely followed the Brexit developments, preparing for several possible scenarios, and started to prepare for the Graphene Flagship's inclusion in the Horizon Europe Framework Programme.

OUR VISION

In Core 3, the next phase of the Graphene Flagship, the Management Work Package will maintain and build upon the excellence of the project, focus on our objectives and keep the efficiency in the project coordination work. This includes ensuring the complementarity with the Experimental Pilot Line and getting ready for the next phase of the project.

WHY IS THE GRAPHENE FLAGSHIP IMPORTANT?

The Graphene Flagship offers a unique format that allows the development of strong collaborations between academia, SMEs and large enterprises across Europe at an unprecedented scale. The project has proven itself an ideal vessel to take ideas from fundamental research to applications in an unprecedented fashion, allowing its partners to cross the valley of death between laboratory research and the market in ways that many have tried but few have succeeded in.

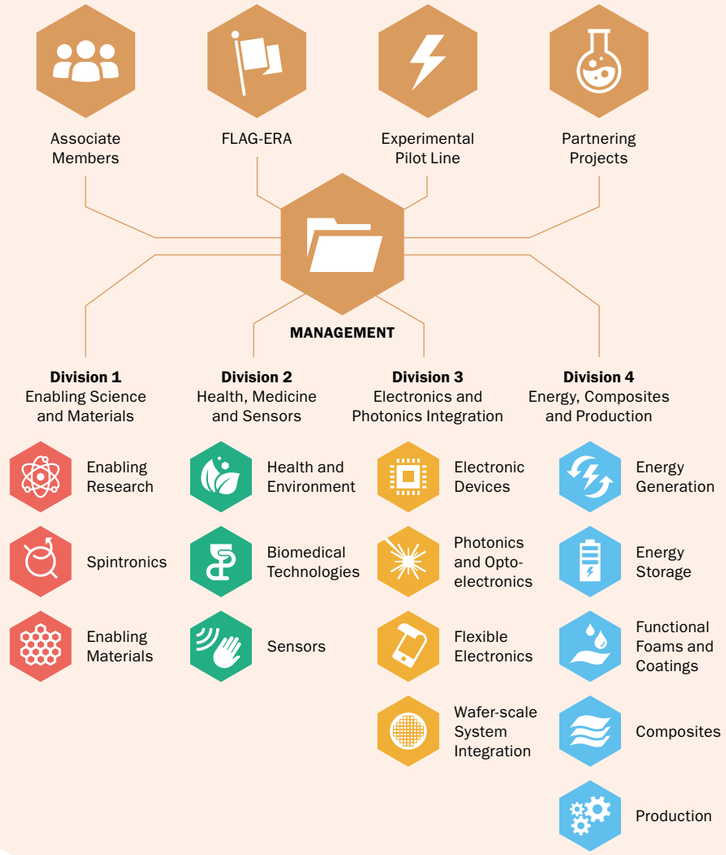
THE PUSH FOR SUSTAINABILITY

In very concrete terms the Graphene Flagship's Management contributes to sustainability through the choices we make. For instance, most meetings of our governing bodies and Work Packages take place online, reducing the need for air travel. On a more strategic level, sustainability influences the decisions we make and the actions we prioritise as demonstrated by Core 3 where initiatives like analysis of environmental effects of graphene technologies, novel energy storage and renewable energy generation, and lightweight and low-energy technologies feature prominently.

Above
Meet our management team, from left to right: Johan Benesch, Macarena Muñoz-Ruiz, Jackie Brown and Flavia Maia. Not pictured: Patricia Huijbers, Madeleine Akbas Tesanovic, Emma Henrikson, Henrik Eidegård and Jari Kinaret. Image credit: Vesa Laitinen

Above
The Management Work Package works with the Partnering Division and the European Science Foundation, organising meetings and events to foster collaborations within the graphene community like the US–EU International Workshop. Image credit: Penn State University

The Management Work Package coordinates every area of the Graphene Flagship, including each research division and all of our Partnering Projects.



Dissemination

Work Package Leader
Vincenzo Palermo, Graphene Flagship Vice Director

Head of Dissemination
Elena Novoselova, Schaffhausen Institute of Technology, Switzerland

Expanding public knowledge of graphene and stimulating collaboration within and outside the Graphene Flagship

Research does not stop once a paper is published. Innovation goes way beyond a product launch, and collaboration blossoms in scientific conferences, tradeshows and meetings. This is why the Dissemination Work Package plays a key role in making the Graphene Flagship such a successful project. We are a multidisciplinary team of experts in science writing, communication, marketing and events, working together to maximise the impact of our project's outcomes.

PROMOTING RESEARCH

If a tree falls in a forest and no one is around to hear it, does is make a sound? Similarly, when the Graphene Flagship publishes important research, will it reach the media?

Our team specialises in promoting research. When results are ready to be published, we collaborate with scientists to craft news stories for our website and engaging press releases for journalists. In 2019, we generated more than 1400 pieces of coverage in printed newspapers, including top outlets like Reuters, The Times, Wired, El País and Corriere della Sera. Our estimated readership online is almost 2 billion and our media appearances have so far saved the project over €17M in paid advertising.

Moreover, we connect with our audience over a variety of social media outlets: we share our content on Facebook to reach the general public, we tweet to stay in touch with the scientific community and policy makers, and we have an active profile on LinkedIn to connect to our business partners and innovation stakeholders. We also target our younger audience through channels like Instagram and YouTube, devoting a portion of our resources to scientific outreach.

Furthermore, the Dissemination Work Package leads the organisation of Graphene Week, Europe's leading conference in the field of graphene and layered materials. Our last edition took place in Helsinki in September 2019, beating previous records of participation and attendance – with three parallel sessions, over 400 poster presentations and almost 700 delegates.

FOSTERING INNOVATION

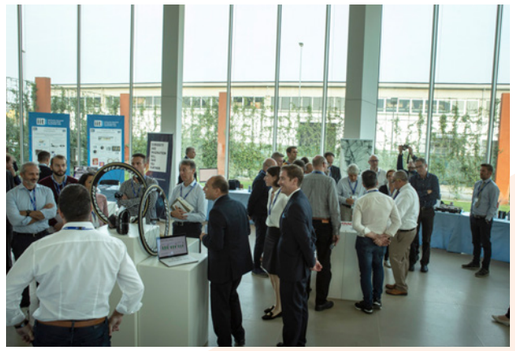
Innovation is the ultimate goal of the Graphene Flagship. Our team collaborates very closely with the Head of Innovation, Business Developers and the Industrialisation Work Package to guarantee that their results are communicated to the appropriate audience – businesses, investors and potential clients. We have focused some of our most important press campaigns on the promotion of innovation. Moreover, we have joined forces with a PR agency that specialises in communicating technological advances and reaching out to B2B magazines. Some of our most successful news stories in 2019 addressed product launches and industry tradeshows like Mobile World Congress or discussed new Graphene Flagship investments in innovation.

On top of that, our experts in Marketing and Events coordinate the Graphene Flagship's participation in large-audience industrial fairs and organise innovation-orientated events, such as our successful Graphene Marketplaces, in collaboration with European industrial leaders. In 2019, our joint event with Tetra Pak gathered over 500 attendees and was broadcast internationally. It resulted in four NDAs, one signed research contract and the strengthening of our relationship with one of the world's leading packaging companies.

Our scientific events are also shifting towards innovation. Graphene Week 2019 in Helsinki had a dedicated innovation branch, as well as an exhibition that attracted industries interested in graphene and layered materials from all around Europe. We now plan to continue to grow this model, and in the next phase of the project, our Work Package will export our successful models to further expand our reach to European industrial communities.

CULTIVATING COLLABORATION

Work Package Dissemination is one of the most collaborative teams in the Graphene Flagship. We are continually in close contact with all scientific Divisions and Work Packages, attending their meetings and events, and we work closely with the administrative groups to foster innovation and industrialisation and deliver the latest news from our management.



Our team has several mechanisms to guarantee that all core partners, Associate Members (AMs) and Partnering Projects (PPs) are represented in our news stories and press releases. We coordinate the Network of National Press Officers, liaising with local communication managers that feed us information from their host institutions, and distributing our materials through their own channels to maximise the impact. Moreover, the SCOPE project, funded by the European Commission, has provided support to our AMs and PPs by communicating their results to society, in close collaboration with our Work Package and the specialised news agency SINC.

The Graphene Flagship's scientific and marketing events also aim to broaden our network. Graphene Marketplaces help us to reach the business community, researchers at our key industrial partners and potential investors interested in graphene-enabled technologies. Graphene Week is also expanding its programme to collaborate with other European institutions and networks (COST, FLAG-ERA, EPO and ESA) and prestigious publishers (Springer Nature, IOP Publishing).

SUPPORTING SUSTAINABILITY AND SOCIAL RESPONSIBILITY

Our team is committed to an open, more diverse and more sustainable project. We collaborate with our Management team to organise two Women in Graphene workshops each year, to challenge gender bias in science, promote gender diversity and provide a support network for professional growth. This initiative will cover an even broader spectrum in the next phase of the project, expanding to Diversity in Graphene and creating new strategies, such as a new mentoring programme, to support underrepresented communities.

We are also closely aligned with the United Nations' Sustainable Development Goals. We are committed to reducing the carbon footprint of our project, favouring online and virtual gatherings in place of in-person meetings, and reducing the number of printed copies of our marketing materials. We are also moving to more environmentally friendly marketing materials, and we will even reduce the production of marketing materials overall.

Students are a key part of the Graphene Flagship community. Not only do we promote their research through our online profile articles, but we also hold a dedicated event specifically for them: Graphene Study. This conference for early career scientists in the field of graphene and layered materials goes beyond scientific contributions, offering a unique learning and networking experience to our promising young researchers.

Our challenge was to communicate the Graphene Flagship's science and technology to industries, institutions and the general public using many media channels at the same time. Thanks to an outstanding team of professionals, we did it."

Vincenzo Palermo

Bottom
Meet our multidisciplinary team of marketing, communications and events experts. From left to right: Sofia Järbur, Rebecca Waters, Elena Novoselova, Luciana Löberg, Tom Foley and Fernando Gomollón-Bel. Not pictured: Melanie Lawson, Letizia Diamante and Vincenzo Palermo. Image credit: Vesa Laitinen

Left page
The Exhibition at our Graphene Marketplace event hosted by Tetra Pak highlighted exciting graphene applications and products. Image credit: Tetra Pak

GRAPHENE FLAGSHIP ANNUAL REPORT 2019

Industrialisation

Work Package Leader
Thomas Reiss, Fraunhofer ISI, Germany

Work Package Deputy
Alexander Tzalenchuk, NPL, United Kingdom

Accelerating the uptake of graphene and layered materials in industry

The key mission of the Graphene Flagship's Industrialisation Work Package is to bring research results to the real world. To this end, the group facilitates and accelerates the uptake of graphene and layered materials in commercial applications through four closely interconnected tasks:

- Exploring, evaluating and forecasting application opportunities based on market needs through the Technology and Innovation Roadmap (TIR);
- Improving trust and confidence in graphene and layered material-enabled products by providing validation services;
- Developing consensus-based and accepted international standards for properties and characterisation of graphene and layered materials, and devices, components and systems enhanced by them;
- Communicating characteristics and specifications transparently *via* the Samples and Materials Database.

2019: A YEAR IN REVIEW

Over the past year, the Industrialisation Work Package continued to monitor the global landscape in order to identify windows of opportunity for Europe. We conducted additional focus investigations on biosensors, water purification, Magnetic RAM and elastomers to identify innovation targets and to elaborate specific value chain roadmaps.

Industrialisation has also worked to create trust and confidence in graphene and layered materials by providing a professional world class Validation Service. In 2019, the service received 38 requests by ten different Graphene Flagship Work Packages. It delivered 30 validation reports (with excellent customer feedback: over 90% of users would use it again and recommend it to a colleague) and regularly developed and rolled out new services to meet the user's needs: four new services were added in the past year.

The Graphene Flagship Standardisation Committee (GFSC) has also worked to position Europe as an innovation leader. The committee has led nine out of 28 international standardisation projects (ISO, IEC).

The Industrialisation Work Package is leading the conversation around graphene innovation. In collaboration with the Innovation Work Package and the Graphene Flagship Science and Technology Officer, Industrialisation set the scene for the industrialisation of graphene and layered materials in a *Nature Nanotechnology* editorial. We also presented and promoted our services widely to international communities at industry days and international conferences, including Graphene Week.

The Work Package is also steering the conversation on the industrialisation of graphene and layered materials within the Graphene Flagship, supporting the initiation of new Spearhead Projects on batteries and solar cells through our value chain roadmapping.

WHY IS THE GRAPHENE FLAGSHIP IMPORTANT TO US?

The Graphene Flagship is a unique international community combining all the elements and actors necessary to bring new material-based innovations to the market and generate benefits for society.

WORKING TOWARDS A SUSTAINABLE FUTURE

All of our industrialisation tasks support sustainability. The Roadmap takes sustainability issues into account in two ways: we explore future application areas that contribute directly to a sustainable future, such as graphene and layered material-enhanced perovskite solar cells or water treatment systems, and our focus investigations highlight the importance of sustainability concepts in innovation.

The measurement data provided by the Validation Service can be used by the requester for Environment, Health & Safety risk assessments. The Validation Service also offers capabilities for ageing, degradation and lifecycle properties assessment, including lifetime duration prediction.

We are committed to increasing confidence and trust in graphene and layered materials and their products, which are prerequisites to adoption by industry, consumers and society, and are vital for the move to a sustainable society.

OUR VISION

The industrialisation workflow established in Core 1 and Core 2 (the Technology and Innovation Roadmap, key performance indicators for graphene and layered materials, the validation and standardisation services and the samples and materials database) will continue to provide a guiding framework for the future path of graphene and layered materials towards markets and society. The Industrialisation Work Package will therefore also enable the Graphene Flagship to communicate its relevance in a convincing way.

A challenge-focused approach to the Roadmap will supplement the current industry sector, market or technology-based approach. This will inform the direction of travel for the Graphene Flagship's future technology developments, allowing it to address grand challenges and Sustainable Development Goals. We will also initiate the expansion of current Roadmap actions in order to anticipate the evolution of the market and to plan and control the technological needs of production. The Industrialisation Work Package will therefore play a coordinating role for global graphene and layered material-based innovation similar to the International Technology Roadmap for Semiconductors (ITRS). We see Europe as having a chance to steer the industry worldwide by taking an early lead in creating an International Technology Roadmap for Graphene (and other 2D materials) (ITRG).

Validation will largely continue as a service, however, the current emphasis on materials will shift to devices in the near future and eventually to the system level. Specifically, in relation to the 2D Experimental Pilot Line, we expect the validation team to play a role in providing independent assessment of its outputs. This independence is important, as it ensures customer confidence.

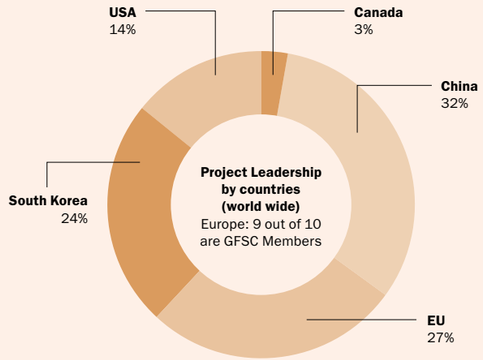
With regard to standardisation, we expect that within a few years the majority of measurement methods will be standardised or well on track to standardisation. Where gaps still exist, for example with the emergence of drastically novel applications or new types of materials, the existing framework of the Graphene Flagship Standardisation Committee will continue its current role. The standardised measurement methods will also inform regulation, particularly concerning the health and environmental aspects of devices and systems enhanced by graphene and layered materials.

REFERENCE

1. T. Reiss, K. Hjelt and A.C Ferrari, Nat. Nanotechnol., 14, 907 (2019)

"The Graphene Flagship is a unique community, combining all the elements necessary to bring new material-based innovations to the market, for the benefit of society."

Thomas Reiss



Right
The Industrialisation Work Package presents and promotes its services widely to international communities at industry days and international conferences, including Graphene Week. Image credit: Vesa Laitinen

GRAPHENE FLAGSHIP ANNUAL REPORT 2019

Innovation

Work Package Leader
Kari Hjelt, Chalmers Industrial Technology, Sweden

Work Package Deputy
Francesco Bonaccorso, Italian Institute of Technology, Italy

Managing, coordinating and supporting graphene innovation

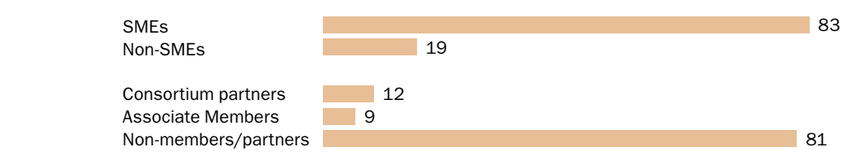
The focus of the Innovation Work Package in the Graphene Flagship is to strengthen the project's cooperation with industry stakeholders in order to increase the technology readiness levels of its outputs.

2019: A YEAR IN REVIEW
Our business developers have actively worked to create the network connecting our research efforts to industry. Their tasks range from scouting the recipients for our technologies to being messengers from industry when it comes to industry trends, needs and roadmaps. They arrange workshops and collaborate with Work Package Dissemination on outreach events like the Graphene Pavilion at Mobile World Congress and the Graphene Innovation Forum at Graphene Week.

Concretely, the business developers served as hosts for the individual sections of the Graphene Pavilion: Phone of the Future, Wearables of the Future and Home of the Future. In this role they introduced the Graphene Flagship's work within their application areas and put the individual demonstrations showcased in the Pavilion into the broader perspective of the project and ongoing graphene innovations. In this way, the business developers act as ambassadors for the Graphene Flagship at the various trade shows and exhibitions we attend.

The seven Graphene Connect workshops organised by Work Package Innovation and aimed at fostering the interest of industries into graphene technologies have been attended by a total of 102 companies. Of these 83 are SMEs and 81 are outside of the Graphene Flagship exemplifying the growing broader industry interest.

Total attending companies: 102

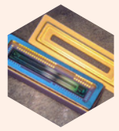


At this year's Graphene Connect & Health Investment Forum, co-hosted by COMB in collaboration with Graphene Flagship partner ICN2, entrepreneurs in graphene technologies had the opportunity to pitch their business project directly to investors and business leaders from the healthcare and medical communities. This novel collaboration with the Health Investment Forum provided a unique opportunity to gain feedback and advice from those currently working in the medical sector, bridging valuable connections between academia and industry.

OUR VISION
In 2019 the Graphene Flagship took another leap in strengthening its innovation efforts: The selection of 11 industry-led Spearhead Projects with application-oriented objectives that are motivated by market opportunities. These Spearheads focus on a wide range of application areas, but all have the common goal of developing new or improved products with integrated graphene or layered materials (learn more about these on page 60).

The Graphene Flagship also announced the creation of the first 2D Experimental Pilot Line. With a budget of almost €20 million over four years, this Pilot Line will pave the way towards commercially competitive graphene products, such as transceivers, photodetectors and sensors.

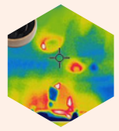
GRAPHENE PRODUCTS
Graphene Flagship partners and Associate Members have released a number of products containing graphene to the market. The business developers play a role in promoting these products and supporting businesses within the project. Here is a sampling of these:



'NIGHT VISION' SENSORS
Emberion introduced a new linear array sensor to detect light in the visible and short-wave infrared spectrum. Thanks to graphene, the sensor is cost-competitive and can be tailored into devices such as spectrometers.
Emberion – emberion.com

NEUTRON 'ROLL TO ROLL'
Neutron is the first roll to roll system capable of depositing large area graphene onto metal foils under ambient conditions. It can be easily placed inline at manufacturing, enabling truly cost-effective graphene production.
Aixtron – aixtron.com

GRAPHENE-ENHANCED SOUND
MediaDevil's earphones are manufactured with a coating of Versarien's Nanene®. This material makes the earphone's diaphragm thinner and more flexible, enhancing the quality of both treble and bass.
Versarien – versarien.com



A 'COOLER' RUBBER
This enhanced rubber integrates graphene materials to increase thermal conductivity. This directly increases heat dissipation in rubber components, and ultimately results in greater product shelf-life and improved performance.
avanzare – avanzarematerials.com

"We are continuing the mission to create a business impact from graphene, and we are now seeing the first wave of graphene-enabled products on the market. The Graphene Flagship's commercialisation activities are moving from material development towards components and system-level integration. In the future, we will see a growing number of high value-added products for various applications."

Kari Hjelt

Left page
Fabrizio Tubertini, business developer for energy applications, speaks to a visitor to the Graphene Pavilion at Mobile World Congress. Image credit: Alexandra Csuport

Bottom
Cinzia Spinato, business developer for biomedical applications, organised the Graphene Connect workshop helping connect entrepreneurs with investors in the healthcare and medical industries. Image credit: COMB

The Graphene Flagship Means Business

There is a growing appetite for start-ups and small companies that have blossomed from research initiatives. Here are five Graphene Flagship SMEs (small to mid-size enterprises) that are setting the pace in the field of graphene commercialisation.

EMBERION – GRAPHENE TO SEE THE INVISIBLE

Emberion develops graphene photonics and electronics that revolutionise infrared photodetectors and thermal sensors. Applications include night vision, X-ray detection, and hyper-spectral and thermal imaging.

Originally, the business was a spin-off company from Graphene Flagship partner Nokia. Following a long history of graphene research inside Nokia's research organisation, the team created Emberion to take the work carried out on optoelectronics to the commercial market.

"Emberion was established in quite an early phase of product development," explained Tapani Ryhänen, CEO of Emberion. "We had promising results and functional prototypes from our research and, above all, we were able to get an agreement with venture capital investors.

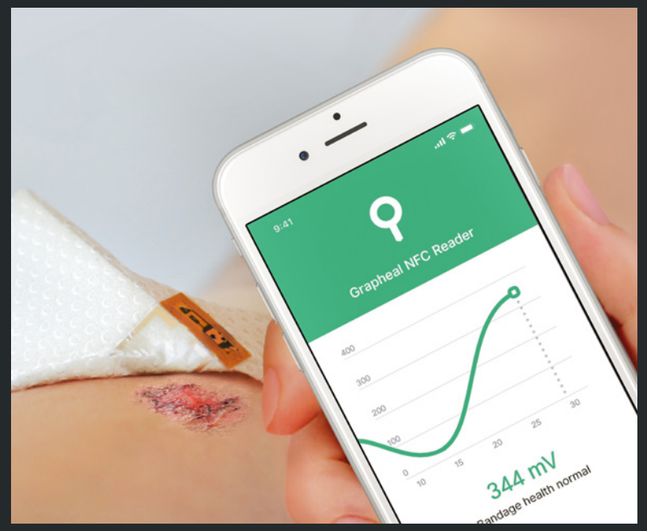
"Emberion is focusing on various spectrometer and machine vision applications by producing novel image sensors. We provide products with broad wavelength range and low noise. Our image sensors can be used, for example, in agriculture, food processing and pharma industries."

Over the next year, Emberion will start delivering its first imager products. The business will also work with the Graphene Flagship GBIRCAM Spearhead Project, together with its partners, to bolster the readiness of graphene-enabled optoelectronics in industry.

GRAPHENEA – A NEW COMPANY FOR A NEW MATERIAL

World leading graphene producer Graphenea, founded in 2010, was one of the first industrial partners to join the Graphene Flagship. Graphenea has collaborated closely with the project since the inception of the EU-funded program and the first proposal stages of this ambitious initiative. Business is booming for Graphenea. In 2018, the business generated €1.6 million, and grew by 25% in 2019.

Graphenea's facilities are located in San Sebastián, Spain and Boston, USA. The 25 employees at Graphenea contribute to the successful development of graphene applications, including supplying CVD graphene films, Graphene Field-Effect-Transistors chips (GFETs), Graphene Foundry Services (GFAB) and manufacturing graphene oxide solutions. Graphenea's operation spans across more than 60 countries and a wide range of sectors.



Below
Grapheal: Grapheal's wearable patch enables continuous monitoring of wounds. Image credit: Grapheal

"The collaboration between Graphenea and the Graphene Flagship has evolved over the last six years," explained Amaia Zurutuza, Scientific Director at Graphenea. "Our work has become incredibly industry-oriented, with focused Spearhead Projects to bring applications to market quickly and effectively.

"Today, we are focusing not only on the production of graphene, but also developing our processing capabilities. Our partnership with the Graphene Flagship provides the support to help reach this goal."

BEDIMENSIONAL – THE POWER OF GRAPHENE

BeDimensional produces and develops graphene and 2D crystals for the manufacturing and energy industries. Its main target applications relate to coatings and paints and material production for energy applications. BeDimensional was created as a spin-off company of Graphene Flagship partner Italian Institute of Technology (IIT) and has now become a Graphene Flagship Associate Member.

The original research group that pioneered the launch of this company started its research in fundamental studies of graphene and layered materials. They were also investigating how to tune the interaction of hydrogen and carbon by curving a graphene sheet. For this latter study, the team were approached in the initial stages of the Graphene Flagship project to set-up a Work Package for hydrogen storage.

After a two-year incubation period within IIT, BeDimensional moved onto the market after the acquisition of 51% of its shares by Camponovo. Then the definitive push towards the path of industrialisation came at the end of 2018, after a €18 million investment from Pellan Group.

So, what's next for BeDimensional? After closing the rounds of investment, this Graphene Flagship spin-off is now fully immersed in implementing its industrial and commercial strategies. The first production line of two-dimensional crystals is already operational, and the business is in the process of setting up more laboratories for research and development.

Together with IIT and leading industrial manufacturer VARTA, BeDimensional is developing graphene-based lithium-silicon batteries with improved capacity and performance. Graphene-enabled batteries, developed within the Graphene Flagship Spearhead on Batteries, have reached the prototyping phase and will soon be tested by electronics manufacturers. This research will be continued in the new GreenBAT Spearhead, which will scale up this technology towards manufacturing graphene-enabled batteries for electric vehicles.

"We need to strategically position ourselves at the right level of the industrial value chains linked to each specific application," explained Vittorio Pellegrini, founder and scientific advisor for BeDimensional. "We believe it is crucial to establish partnerships and joint ventures with appropriate global players. At the same time, we will reinforce our investment in R&D by attracting the best people on board."

GRAPHEAL – GET WELL SOON… WITH GRAPHENE

Chronic wounds can take months or even years to heal. In one out of five cases, the injury never heals and can lead to a limb amputation. Evidence suggests that effective wound care will become critical for healthcare in Europe as the population ages and the prevalence of chronic wounds increases.

That is why Grapheal has developed a pioneering wearable patch for the remote monitoring of chronic wounds. The flexible and transparent graphene-based biosensor enables doctors and nurses to provide hyper-responsive treatment of chronic wounds. Grapheal is a spin-off from CNRS-Grenoble, France, and has joined the Graphene Flagship as an Associate Member.

Connected to a smartphone, Grapheal's wearable patch enables continuous monitoring of wounds, to empower caregivers and wound sufferers with a smart and accurate assessment tool. The wound patch measures and stores the bio parameters of the wound and communicates this data to the cloud *via* a smartphone app. This real-time connectivity ensures nurses and doctors can be alerted to early stages of infection and other complications.

"Our patented formula uses Graphene-on-polymer, in a non-invasive way, to actively react to any changes to the wound", explained Vincent Bouchiat, Grapheal CEO. "As an atomically thin material, graphene's electrode conductivity will change according to any physicochemical change, enabling faster detection of problems for patients."

"Our patch can adapt to any shape of wound, using Graphene's thin and flexible properties. In fact, the non-invasive nature of the patch actively stimulates wound healing – and we have led eight preclinical studies to prove its bio stimulation properties."

PAYPER – GRAPHENE TRANSFORMS TABLE PAYMENTS

Payper is a new spin-off company that has launched an innovative payment method using graphene-enhanced receipts. Users simply place their phone on the restaurant bill and a payment screen appears in seconds, without the need to download an app.

Payper uses graphene's unique properties to manufacture a special paper with embedded NFC antennas. The restaurants then use it to print the restaurant bill, enabling phones to interact and immediately receive a digital version of the receipt, and instructions for payment. In less than five seconds, a window appears on-screen, allowing customers to settle the payment in two clicks, without having to wait for staff.

"After spending ten years on advanced material research, we saw a clear opportunity to use graphene to enhance the payment process. Graphene could solve the issue of card terminal jams and downtime, allowing restaurants to run their operations more quickly, and at a reduced cost," explains Payper co-founder Renate Kalnina.

"Now that we have manufactured the graphene antenna rolls, we then built the necessary software to handle the payments. We are now in discussions with multiple restaurants who have expressed an interest in trialling the technology."

Payper
Payper has developed an innovative payment method using graphene-enhanced receipts. Image credit: Payper

Production

Work Package Leader
Alex Jouvray, Aixtron Ltd., United Kingdom

Work Package Deputy
Tamara Blanco, Airbus, Spain

Producing new materials for aerospace, fire protection, corrosion prevention and more

Our Work Package is largely made up of industrial partners who use graphene to develop and improve the performance of commercial products. This includes UV-C LEDs for water purification, coatings for copper wires to improve conductivity, new composites for fire protection in vehicles and buildings, and new materials for the aerospace industry. In particular, we produced and validated new materials for the Airbus A350 aircraft.

In addition to product development, our partners have significantly increased the production and distribution capabilities of graphene and layered materials for the entire Graphene Flagship. Our materials are made using standardised, quantified and certified methods to ensure we meet the levels of consistency and reproducibility required for product development.

BETTER THAN THE BEST, WITH REAL IMPACT

We run four key tasks, each addressing a different market. In each of them, graphene enhances the properties and performance of our products to the point that they exceed current state-of-the-art technology.

- UV-C LEDs: We exploit the conductive and optical properties of graphene to create a transparent electrode for UV-C LEDs, with improved efficiency, for water treatment and purification.
- i-cables: Copper wires are coated with graphene to improve both conductivity and corrosion resistance, extending their shelf life and enabling them to be thinner and lighter.
- Aerospace materials: Graphene enhances the impact resistance of construction materials for aircraft, like in the Airbus A350. After testing and upscaling, this could provide significant benefits to safety, fuel efficiency and weight reduction, which in turn will decrease the environmental impact.
- Fire protection: The coatings and structures we develop using graphene and layered materials can be used in both the automotive industry and in building construction. Not only do they provide fire protection, but they also have diagnostic fire sensing capabilities: a significant health and safety improvement compared to existing materials.

BREAKING INTO INDUSTRY

The Production Work Package's developments are mostly carried out by commercial organisations, such as our European partner companies Airbus, Aeronova and Grupo Antolin.

As such, all of our developments are industry-driven and contribute to the Graphene Flagship's goal of industrialisation. We make graphene on a much larger scale than in research and development, and all of our graphene producers are ISO certified. The graphene prepared by our partners is also subject to strict process control.

For example, the materials we manufactured for the Airbus A350 meet the manufacturing quality standards required for commercial aircraft. Furthermore, we are performing full-scale experimental bird impact tests to fully evaluate the durability of the graphene-reinforced structure under working conditions.

In terms of fire protection, we scaled up the production capability of our flame-retardant materials to an industrial level, making large volumes of composites and paints. In addition, validation tests were done according to international standards, and the high availability of our materials enables them to be used in a broader range of applications, subsequently raising the technology readiness level.

2019: A YEAR IN REVIEW

We performed more than 100 compression after impact tests on industrially relevant-sized samples of our aerospace materials. As little as 1.2% graphene and layered material can improve impact resistance by more than 9% compared to conventional laminate materials.

By applying graphene and layered materials to flame-retardant paints, we reduced the temperature of a standard steel frame, common in modern buildings, by over 150°C when exposed to fire. Finally, we successfully developed a new graphene growth process under atmospheric pressure to enhance the performance of copper wires. We demonstrated this using a batch processing tool, resulting in a ~1% increase in conductivity.

OUR VISION

In the next phase of the project, we will release more products, develop continuous quality control processes, and implement solutions for the integration of graphene into the mass market.

We will explore the use of graphene and layered materials for more applications in aerospace, such as structural health monitoring. We will also develop smart systems for industrial applications in pipes, tanks and reactors, with the potential to be used for corrosion protection, which today accounts for ~3.5% of the global GDP.

The four markets addressed by the Production Work Package. Graphene enhances the performance and properties of these products beyond the state-of-the-art.

In each of our products, graphene enhances the properties and performance to the point that they are better than current state-of-the-art technology."

Alex Jouvray

Left page
The materials we create are rigorously qualified and quantified in line with industry-certified standards

Bottom
Graphene Flagship scientists hard at work developing new materials for industry using graphene and layered materials. Image credit: Bedimensional Spa

Composites

Work Package Leader
Costas Galiotis, FORTH, Greece

Work Package Deputy
Ian Kinloch, University of Manchester, United Kingdom

Developing new composites for industrial applications based on commercial demand

Our Work Package develops high-performance composites using graphene and layered materials that meet the high standards required by industrial sectors such as the aerospace, automotive and energy generation industries. We incorporate graphene and layered materials into various different matrix combinations, from thermoplastics and thermoset composites to elastomers and inorganic composites.

DRIVEN BY MARKET DEMAND

Our Work Package is motivated by the demands of the commercial market. We have adopted a value chain strategy to establish synergy between the needs of the end users and the state-of-the-art knowledge developed by our academic partners. This philosophy helps us to achieve our goal of creating more cost-effective products with higher technology readiness levels, for rapid transition from the laboratory to the market.

In particular, we are working on the following market-driven composite technologies:

- Low-cost, quality-controlled masterbatches of polymer pellets enhanced by graphene and layered materials, for widespread use in the plastics industry.
- Fibre and fibreglass-reinforced polymer composites with lower weight, higher thermal and electrical resistance, and improved mechanical strength and stiffness. These materials could reduce fuel consumption, emissions and assembly costs in the aerospace and automotive industries.
- Elastomers with improved flexibility and strength, lower shrinkage, better wear resistance and higher chemical resistance and thermal stability – with applications in the aerospace and automotive industries as well as in sensors, robotics, thermal dissipation, fire protection, water resistance and power distribution.
- Composites containing inorganic components, such as metallic powders, nanoparticles or nanofibers, to improve the efficiency of conductors, create coatings for environmental protection and design new components for additive manufacturing. These materials could improve the thermoelectric properties and lifetime of construction materials and reduce assembly time and cost in all of the above industries.

2019: A YEAR IN REVIEW

We filed and were granted six new patents on composite products developed by our Work Package. We showcased our materials at a number of conferences and exhibitions around Europe, including the Graphene Marketplace event hosted by Tetra Pak in Italy, MATCOMP 2019 in Spain, and K Düsseldorf in Germany – the largest exhibition fair for elastomers and thermoplastics.

Furthermore, we prepared and demonstrated a number of prototypes, such as:

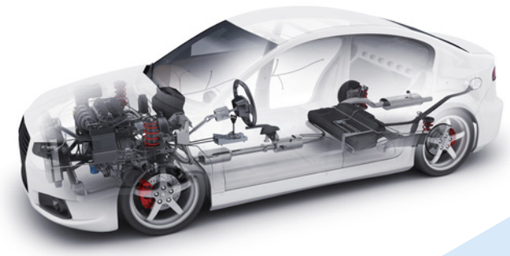
- A number of scaled-up functionalised graphene masterbatches in various matrices, reaching a technology readiness level of eight.
- An extrusion system to produce composite filaments and fibres at a rate of 1 kilogram per hour.
- Bulk thermoplastics for anti-icing applications.
- 3D-printed copper-graphene oxide composites.

We also took part in the Graphene Flagship's Parabolic Flight Campaigns, as well as conducting sounding rocket experiments to test graphene-based wicks and printing under microgravity conditions. We also tested graphene-based loop heat pipes for low-power satellite cooling at Graphene Flagship partner company Leonardo in Italy.

Finally, we developed a new theory for the differences in performance of graphene and layered material nanocomposites between those with low modulus, such as rubber, and those of high modulus, such as epoxy resins.

WORKING WITH KEY INDUSTRIAL PLAYERS

In total, we have established 23 new academic-industrial collaborations. The close relationships with our partners, including academics, small and medium enterprises and large multinational industries, have led to a number of real products and demonstrations.



For example, our carbon fibre epoxy composites have already been integrated into the aerospace supply chain. In addition, we worked with German chemical company and Graphene Flagship partner BASF to develop new routes to flexible thermal connectors. We also established a spin-off company, AVA – a commercial supplier of graphene and layered material-enhanced composites developed within our Work Package.

MORE SUSTAINABLE THAN CONVENTIONAL MATERIALS

Our composites can offer more sustainable solutions due to their long service life, lower maintenance and assembly costs, and energy saving potential as a result of their weight reductions and enhancement in mechanical performance.

Not only this – graphene and layered materials are able to bestow multi-functionality to composites, such as thermal or electrical conductivity, thus making additional materials and components obsolete. This leads to further savings in terms of weight and assembly, maintenance and manufacturing costs. They can also improve the durability of host materials by acting as coatings to enhance service life and enable even further energy savings by reducing thermal dissipation in electronic devices and providing EMI shielding.

OUR VISION

The global market for lightweight materials is expected to grow, so there is great demand for new composites with increased performance, reduced cost, multifunctionality and recyclability – particularly in the automotive and aerospace industries.

Hence, in the coming years, the main objective of the Composites Work Package is to develop new graphene and layered material composites beyond the prototype stage, with selected systems being taken through to high technological maturity – with readiness levels between seven and nine.

We also expect further development of commercial prototypes and products based on graphene-filled elastomers with enhanced wear-and-tear resistance for use in pneumatic tires, engine seals and belts.

Our composites can offer more sustainable solutions due to their long service life, lower maintenance and assembly costs, and energy saving potential as a result of their weight reductions and enhancement in mechanical performance."

Costas Galiotis

Left page
Components made using lightweight graphene fibre composites, in collaboration with Fiat-Chrysler, could help the Graphene Flagship develop the car of the future

This
The Graphene Flagship worked with Airbus to implement a plan-of-action to make sure graphene-based materials fly as soon as possible

Functional Foams and Coatings

Work Package Leader
Xinliang Feng, Technical University of Dresden, Germany

Work Package Deputy
Paolo Samori, University of Strasbourg, France

Developing new foams and coatings for environmental remediation

We design, research and develop new technologies for next generation foams and coatings, based on graphene and layered materials, for environmental applications such as water and air purification, anti-corrosion coatings, and humidity and pressure sensors for environmental remediation.

The ultimate goal of the Functional Foams and Coatings Work Package is to develop new technology to help EU countries mitigate climate change in line with the Paris agreement, and to enable these countries to adhere to policies set by the European Commission defining acceptable standards for water and air quality.

2019: A YEAR IN REVIEW

We made a number of important advancements over the year that we are pleased to report. Three highlights are as follows:

- We developed graphene and layered material-based electrodes for capacitive deionisation, a method for removing salt from water by applying an electrical potential difference over two electrodes. Our new system can remove over 60% of the salt from sea water.
- We formulated ‘smog-eating’ coatings based on titania functionalised with graphene and layered materials, which absorb pollutants from the air.
- We developed new systems for water and air filtration based on graphene and layered materials and launched two new industry-focused projects for the next phase of the Graphene Flagship: AEROGrAFT and GRAPHIL, in collaboration with Lufthansa Technik and Medica.

GREENER SCIENCE FOR A CLEANER PLANET

Sustainable development is the main focus of our Work Package. Our graphene foams and coatings for water desalination, and air and water purification, can address the demand for clean water in developing countries and help to reduce the effects of pollution, which will be extremely valuable in built-up urban environments.

Foams and coatings can not only yield drinkable water, but they can also provide suitable water for agricultural uses from sea water. The technologies we developed using graphene and layered materials are more economically efficient than existing methods, such as reverse osmosis.

Similarly, our air purification devices are more efficient than the current state-of-the-art, such as activated carbon. Our devices can also remove a broader range of pollutant types, and they are self-cleaning: thereby reducing the CO_2 footprint and lowering the maintenance cost of repairing or replacing them.

WHY IS THE GRAPHENE FLAGSHIP IMPORTANT TO US?

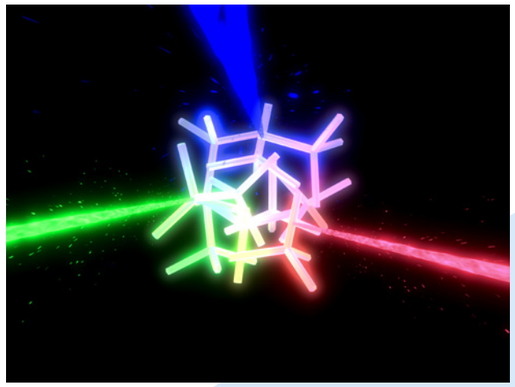
The sheer scale of collaboration between different scientific and industrial partners, enabled by the Graphene Flagship, is unprecedented. The continuous support enables us to transfer the knowledge we gain from laboratory research to product innovation, and eventually to commercialisation. Furthermore, the partnerships fostered by the Graphene Flagship enable us to synergise with other Work Packages, allowing us to further advance our research along this pathway and establish a number of spin-off companies.

An example is Sixonia Tech GmbH: a graphene production and processing company founded in Dresden, Germany, in 2017. Sixonia makes functionalised graphene and formulations such as inks and pastes. The company’s inception would not have been possible without our collaboration with the Enabling Materials and Energy Storage Work Packages, all thanks to the Graphene Flagship.

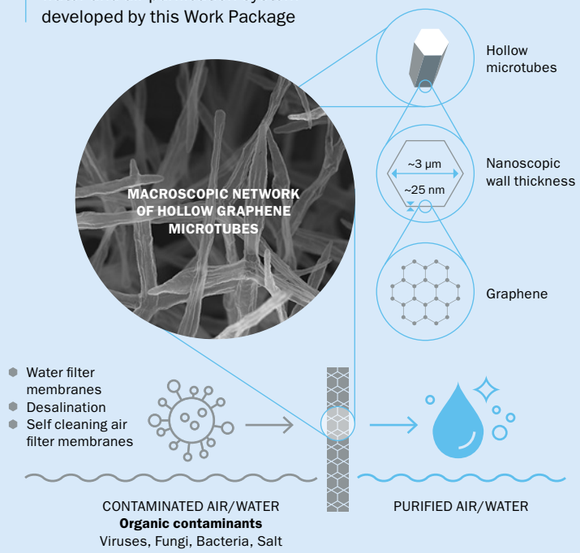
OUR VISION

Over the next few years, our Work Package will introduce the technology we have developed in water and air purification to the market. Thanks to our close partnership with important industrial partners, like Lufthansa Technik, we are able to break into the commercial market and establish a strong presence.

We will also extend our research activities to other key fields in environmental remediation, such as oil spill removal, and the creation of self-powered water desalination devices.



Schematic of the graphene-based water and air purification system developed by this Work Package

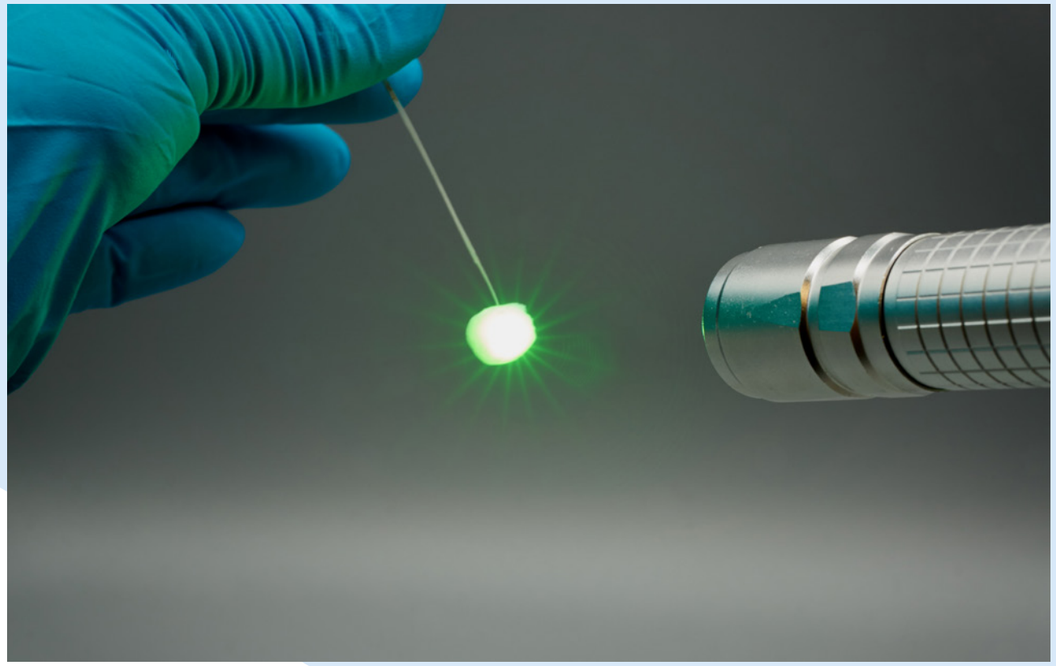


Our graphene foams and coatings for water desalination, and air and water purification, can address the demand for clean water in developing countries and help to reduce the effects of pollution.”

Xinliang Feng

Left page
Graphical representation of the aero-BN diffuser exposed to three laser beams. Image credit: Fabian Schütt

Bottom
Lightweight aero-BN foam used to scatter a directional laser beam in all directions. Image credit: Florian Rasch



Energy Storage

Work Package Leader
Vittorio Pellegrini, IIT, Italy

Work Package Deputy
Teófilo Rojo, CIC EnergiGUNE, Spain

Developing batteries and supercapacitors based on graphene and layered materials

In the Energy Storage Work Package, we develop and improve energy storage technologies by integrating graphene and layered materials into supercapacitors and batteries. In particular, our work covers the following areas:

- Designing and constructing lithium ion batteries using graphene-silicon anodes, which outperform available commercial products.
- Devising novel, more sustainable solutions based on graphene and layered materials, compatible with our innovative spray-coating roll-to-roll technology, to make supercapacitor electrodes.
- Developing alternative technologies for a new generation of lithium-sulfur and metal-air batteries.

CHARGING TOWARDS COMMERCIAL APPLICATIONS

We are working towards bringing established energy storage technologies, such as lithium ion batteries and supercapacitors, to a new level of performance in terms of power and energy density, stability and temperature range – as well as minimising the environmental impact. We do this by exploiting the favourable properties of graphene and layered materials as components in composite materials for electrodes.

We also work closely with our partner companies, and thanks to this collaboration, the potential to scale up our technologies and release real products in the short-to-medium term is very high.

COLLABORATING WITH NEW AND ESTABLISHED COMPANIES

In order to achieve scaled-up products, we are developing new European value chains. Over the years, we have ramped up our collaboration with European partner companies such as VARTA, based in Austria and Germany, and Thales, based in France. At the same time, we have attracted additional companies to join the consortium, like M-Solv and LITHOPS.

The contributions to our Work Package's efforts from industrial partners will continue to rise in the next phase of the project, when European manufacturing and material production companies BeDimensional, Graphenea and NAWA will join the Graphene Flagship. Thanks to our heavy involvement with industry, our high-level of focus and commitment to researching and developing next-generation energy storage technologies will continue for the foreseeable future.

2019: A YEAR IN REVIEW

We made great progress in 2019, with some important developments in alternative technologies to conventional batteries. We are excited to report the following:

- An industrial prototype of a lithium ion cell using a silicon-graphene anode
- A large-area spray-coating process with a nanostructured carbon-graphene liquid solution for electrodes in supercapacitors
- Reversible and stable lithium-sulfur batteries with high areal capacities
- Graphene-based aerogels as electrodes for sodium-air batteries

We will soon be exploring the industrialisation of our silicon-graphene anodes in lithium ion coin cells, in collaboration with our partner company VARTA. This technology has great potential for commercial applications in fitness trackers, in-ear headphones, small biomedical devices and more. We will also extend the technology to the automotive sector.

WHY IS THE GRAPHENE FLAGSHIP IMPORTANT TO US?

The Graphene Flagship offers advantages significantly greater than any other shorter, smaller scale collaborations: the possibility to develop a long-term strategy that is shared equivalently across a large research and industrial community.

We are very fortunate to have a wide variety of scientists with a broad range of expertise, a high level of competence and access to a vast array of equipment. Ground-breaking research, development and implementation requires a critical mass of combined input and collaboration – and the Graphene Flagship helps us to reach that point.

The sheer determination of everyone involved in the Graphene Flagship enables us to increase the competition of our products on an industrial scale, and develop new, effective strategies for research and development in years to come.

WORKING TOWARDS A SUSTAINABLE FUTURE

Improving energy storage devices is an important step forward if we are to progress towards a sustainable world. Efficient and reliable energy storage will be vital for us to increase our dependence on renewable energy and move away from fossil fuels.

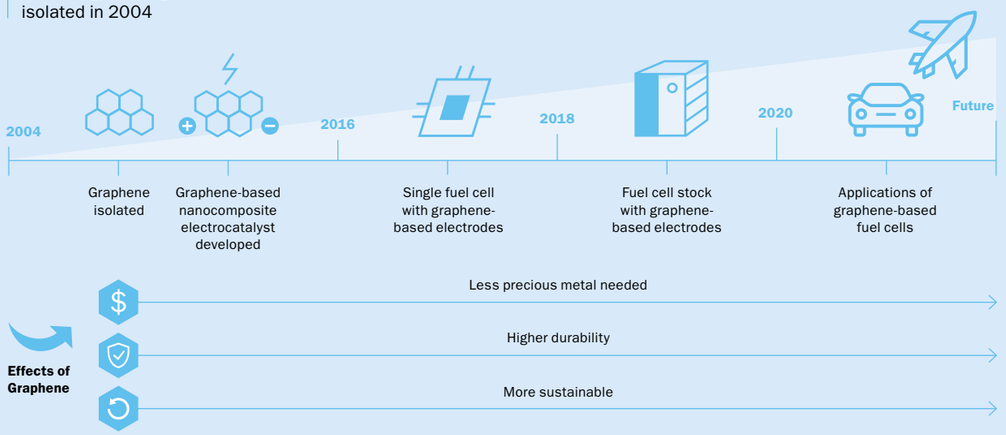
Part of our work on future technologies also explores the role of graphene in the creation of electrodes that use more abundant and sustainable materials like silicon, sodium and sulfur for metal-ion batteries.

We are also working on integrating the most sustainable materials produced by our industrial partners into our devices and making efforts to develop alternative methods of electrode processing that circumvents the need for organic solvents and known pollutants.

Efficient and reliable energy storage will be vital for us to increase our dependence on renewable energy and move away from fossil fuels."

Vittorio Pellegrini

The effects of graphene on energy storage technology since graphene was first isolated in 2004



Left page
Graphene-enabled silicon batteries for wireless headphones, hearing aids, wearables, and small electronic devices, recently developed by VARTA. Image credit: VARTA

This
Our Work Package aims to use graphene and layered materials to open the door to a new generation of ways to store energy

Energy Generation

Work Package Leader
Gérard Gebel, CEA, France

Work Package Deputy
Emmanuel Kymakis, Hellenic Mediterranean University, Greece

Developing industrially competitive photovoltaic panels and hydrogen fuel cells

The aim of the Graphene Flagship's Energy Generation Work Package is to fabricate new graphene and layered material-based photovoltaic panels and hydrogen fuel cells.

Our objective is to develop large-scale competitive systems for both of these technologies, which already exist as industrial-scale products. We do this by designing new materials and production processes to obtain better performance values, longer stabilities and lower costs when translated to an industrial scale.

We are closely collaborating with several Graphene Flagship partner companies: Italian-based manufacturing company Breton, photovoltaics manufacturer GreatCellSolar and graphene-based fuel cell and catalyst development company Amalyst.

Thanks to the Graphene Flagship and our partnership with these companies, we have achieved several record-breaking devices with performance values that are better than the state-of-the-art.

OUR QUEST FOR SUSTAINABLE ENERGY

Primarily, we focus on the photovoltaic activities of perovskite solar cells. We use layered materials, such as molybdenum disulfide, to improve the performance and long-term stabilities of these cells. We have even launched an industry-targeted project to develop a solar farm in Crete.

We are working on proton-exchange membrane fuel cells (PEMFCs), using graphene and layered materials to reduce production costs significantly, and replace the need for platinum as a catalyst. These environmentally friendly fuel cells transform the chemical energy from the reaction between hydrogen and oxygen into electrical energy.

Furthermore, we also use graphene-based materials as a support for catalysts in these devices, or to synthesise new types of alternative materials.

Finally, we are using graphene and layered materials as electron-conductive anti-corrosion coatings for bipolar plates in PEMFCs, to replace the usual gold coating – meaning PEMFCs can be produced more sustainably, potentially with better durability and lower cost.

2019: A YEAR IN REVIEW

We achieved large-scale production of solar cells with excellent performance. We are also hard at work on the development of the Crete solar farm.

2019 was also a great year for our work on fuel cells, as we successfully scaled-up the assembly of membrane electrodes and achieved better performance than a state-of-the-art reference catalyst.

WHY IS THE GRAPHENE FLAGSHIP IMPORTANT TO US?

Our Work Package and our partners are certain that graphene and layered materials are a great opportunity to improve photovoltaic and fuel cell technologies. The Graphene Flagship continuously sustained our research effort for several years, and will do for many years to come. This allowed us to identify and select promising materials and develop them further, on a large scale, to increase the technology readiness levels of our devices.

In addition, the Graphene Flagship facilitates continual and close collaboration between partners and other Work Packages with both complementary and widely different skillsets. The efficiency and productivity enabled by this is crucial to our research and to the development of the field.

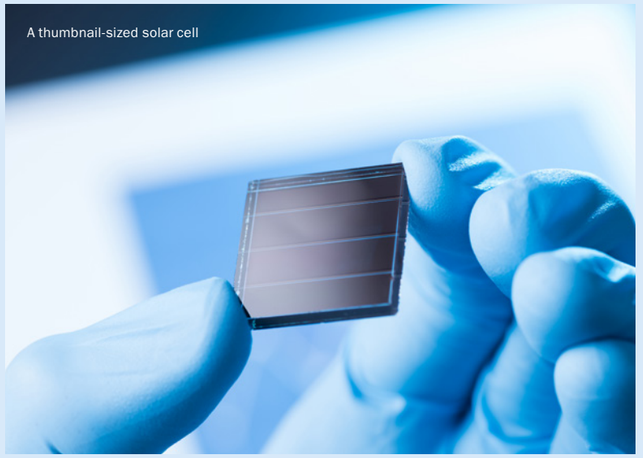
Aerial drone view of solar panels at a solar energy generation farm

OUR VISION

At the end of the next phase of the project, we anticipate that flexible printed photovoltaics and fuel cells, enabled by graphene and layered materials, will reach technology readiness levels of six to eight. These advances will allow us to create working demonstrations and increase the viability of market-penetrating products.

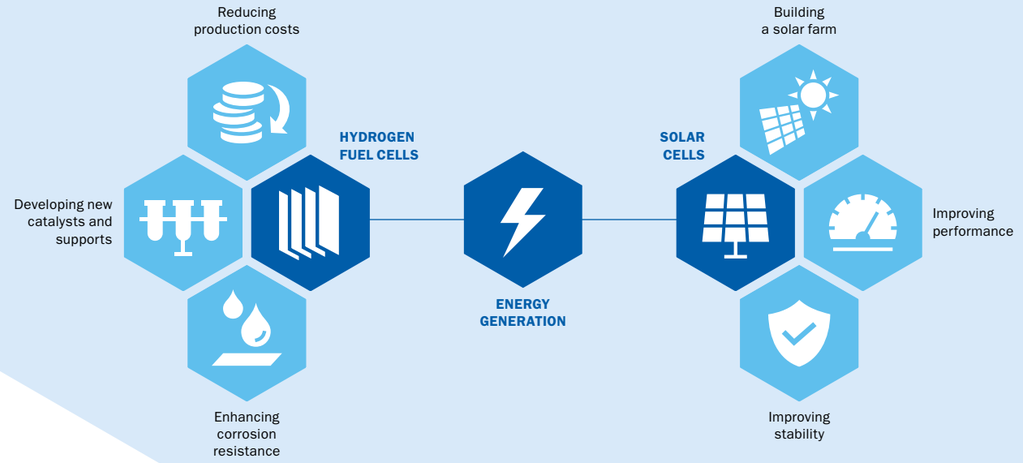
In collaboration with the Energy Storage Work Package, we will develop autonomous, smart Internet of Things devices and wearable prototypes. These devices may be self-powered, taking advantage of our photovoltaics and supercapacitor technologies, and may incorporate RF harvesting for energy conversion.

Going forward, we will develop working demonstrations of our technologies, including graphene and layered material-based fuel cells for forklifts and cars, and power plants for households.



A thumbnail-sized solar cell

The two key markets in focus of the Energy Generation Work Package



The Graphene Flagship's support has allowed us to identify promising materials for energy generation and develop them further, on a large scale, to increase the technology readiness levels of our devices."

Gérard Gebel

Core 2
Spearheads Cross the Finish Line

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 Samori
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

GRAPHENE FLAGSHIP ANNUAL REPORT 2019

Wafer-Scale System Integration

Work Package Leader
Marco Romagnoli, CNIT, Italy

Work Package Deputy
Cedric Huyghebaert, IMEC, Belgium

Integrating graphene into silicon wafer manufacturing processes

Incorporating graphene into microelectronic components, like memory chips and processors, or photonic components for data communications, can enhance their performance in terms of size, power, energy efficiency and more. This is crucial for the next generation of photonic, optoelectronic and high-frequency electronic devices.

But integrating graphene and layered materials into scaled-up manufacturing processes is a challenge, and this is necessary for graphene-integrated circuitry to be fabricated on an industrial scale. This can be done using wafer-scale system integration: the process of building large integrated circuits, on an entire silicon wafer, from the bottom up.

In our Work Package, we tackle this challenge head-on. We focus on the development of innovative solutions for wafer-scale integration with graphene, for a wide range of electronics, optoelectronic and photonic applications.

FROM LAB TO FAB

The wafer-scale integration of graphene into electronic and photonic devices requires us to develop a transition from the laboratory to the fabrication line. Our research has demonstrated that graphene can be integrated into the silicon fabrication processes, and by doing this, we can transfer the properties of graphene into wafer-scale production.[1,2]

The scope of our Work Package is to find new scientific and technological solutions to make graphene compatible with existing wafer-scale fabrication processes, especially those producing integrated circuit chips. We are working on methods for growth and transfer of graphene onto a large wafer, up to 300 mm in size, and developing the technology to integrate it while preserving its quality, integrity and high carrier mobility.

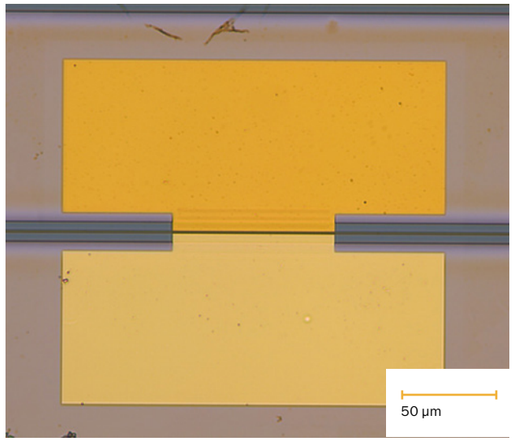
2019: A YEAR IN REVIEW

We focused on the transfer of graphene to silicon wafers and fully functioning photonic and electronic devices, fabricated using wafer-scale approaches. We also successfully demonstrated a high-performance and reproducible photonic chip for optical communications.

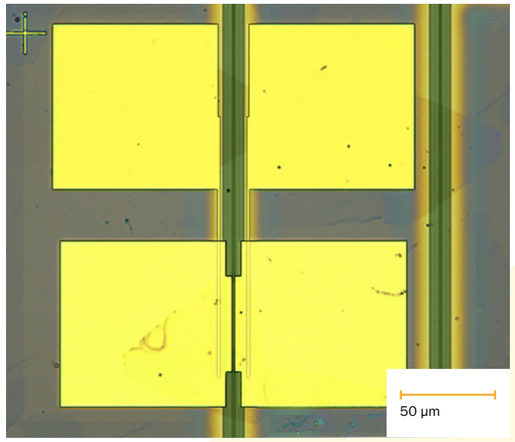
BREAKING INTO INDUSTRY

At our Work Package's inception, we faced the usual challenges related to breaking into a new technology. Our work on the wafer-scale approach has been fruitful, and we have already produced working examples of wafer-scale photonic and electronic devices.

Below
Optical micrograph of a fabricated double layer electro-absorption graphene modulator. Image credit: CNIT/IIT



Below
Optical micrograph of a fabricated double layer photothermoelectric graphene photodetector. Image credit: CNIT/IIT



Using a wafer-scale approach in fabrication not only allows manufacturers to make devices in large quantities, but the reproducibility and uniformity of the production methods also results in high-quality individual devices.

We also developed a tool based on terahertz absorption to rapidly measure mobility and other important parameters in wafers, and for on-line diagnostics of process quality. This allows us to map the carrier mobility of graphene integrated on wafers, which is crucial for applications. Using this diagnostic tool will help us to ensure the consistency and quality in production, saving valuable testing time.

Our work will improve the technology readiness level and eventually lead to the industrial-scale production of graphene-integrated electronic, optoelectronic and photonic chips.

WORKING TOWARDS A SUSTAINABLE FUTURE

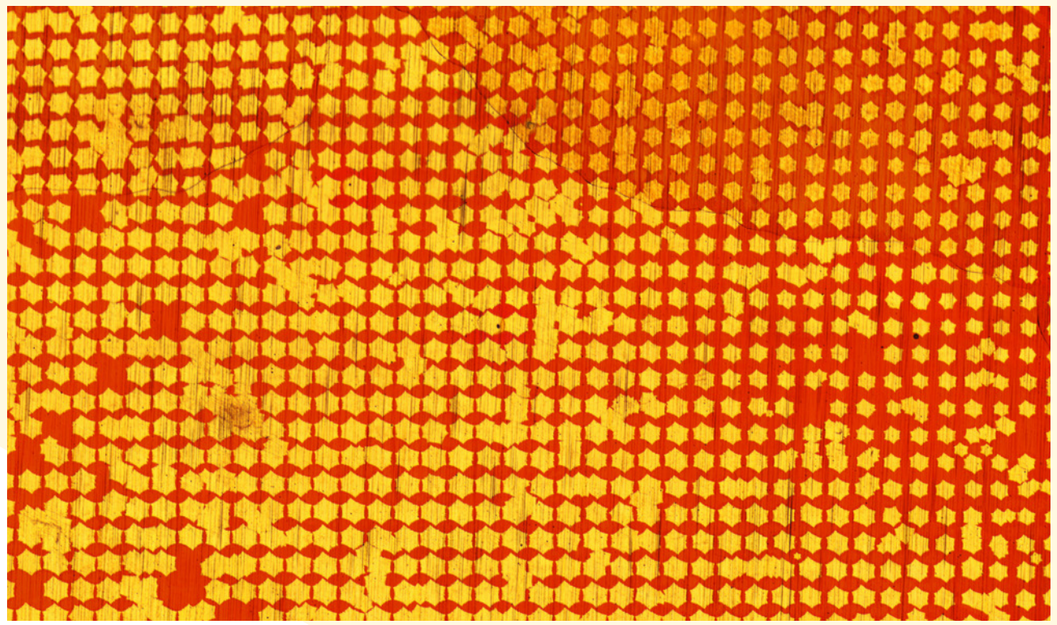
Carbon is one of the most abundant materials on Earth. In our Work Package, we make use of carbon in the form of graphene as a substitution for many functionalities in electronic circuits that usually require rarer materials with dwindling supply, such as indium, gallium, arsenic and germanium.
It is also significantly cheaper and easier to recycle carbon than the rare and precious metals commonly used in electronic components. There may be a shortage of these metals in years to come, so our Work Package's development of graphene as an alternative may be integral to the future of electronics, optoelectronics and photonics.

REFERENCES

1. M. Romagnoli et al., Nat. Rev. Mater., 3, 392 (2018)
2. D. Akinwande et al., Nature, 573, 507 (2019)

> Integrating graphene into optoelectronic, photonic and electronic devices could greatly improve their performance. With wafer-scale integration, we could extend the benefit of graphene to large production volumes."
>
> Marco Romagnoli

Bottom
Microscopic photograph of wafer-scale graphene crystals grown on copper. We can control the position of crystal growth on the catalyst, and this technology is specific to the Graphene Flagship. Image credit: CNIT/IIT



Flexible Electronics

Work Package Leader
Maria Smolander, VTT, Finland

Work Package Deputy
Henri Happy, University of Lille, France

Sustainable development of electronic circuits on flexible, stretchable or conformable substrates

The aim of our Work Package is to demonstrate the viability of graphene and layered materials for applications in flexible electronics. We do this by developing functional prototypes that perform better and are more reliable than current state-of-the-art devices, or provide advantages in terms of consumer appeal, business appeal or environmental friendliness.

We carry out our research and development on graphene flakes for printed electronics, and on grown and transferred graphene and layered materials for high-performance flexible devices.

Over the past few years, we have developed a number of new sensors, prototype wearable autonomous devices for health monitoring, interactive printed electronic products based on paper and transparent electrodes to be used in the automotive industry.

GETTING NEW TECHNOLOGY ON THE MARKET

Flexible electronics are electronic circuits on flexible, stretchable or conformable substrates. These can enable new and unconventional products like smart textiles, interactive skin patches and lightweight large-area electronics.

The main applications are in the automotive, consumer electronics, packaging and advertising, and pharmaceutical and healthcare industries. In the coming years, more and more flexible, lightweight and mobile products will hit the market.

Graphene and layered materials have unique and valuable properties: in particular, mechanical robustness, conformability, sustainability, low-toxicity and low-cost large-area production. Flexible electronics are a great way to take advantage of these properties. Designing new devices based on graphene and layered materials could allow us to get new products from the laboratory to industrial-scale commercial production.

WORKING WITH KEY PLAYERS IN INDUSTRY

Thanks to our collaboration between academic and industrial partners, our developments have come a long way.

We worked with graphene-based photonics and electronics company Emberion to produce flexible X-ray detectors, and with Nokia to produce an autonomous wearable sensing device. We have also made great progress in paper-based interactive devices and transparent touch panels.

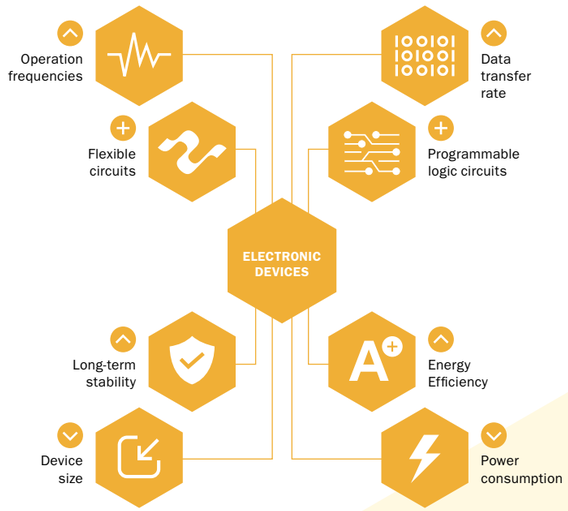
2019: A YEAR IN REVIEW

Our demonstrations of working devices have garnered a lot of attention, and we have shown the applicability and potential of graphene over a diverse range of applications. We had a strong presence in 2019, and showcased our developments at Mobile World Congress, Graphene Week and the Graphene Marketplace event hosted by Tetra Pak, the world's leading food packaging and processing company and Associate Member of the Graphene Flagship.

At Mobile World Congress 2019, we presented several working prototypes: a memo board to store and play messages, a board game with capacitive touch capabilities and a multi-segment display, and a touch-sensitive T-shirt with a printed graphene-based capacitive touch panel.

We also developed a high-sensitivity pressure sensor for health monitoring, based on graphene oxide.[1]

Developments within the Flexible Electronics Work Package could enhance many different aspects of electronic devices



WORKING TOWARDS A SUSTAINABLE FUTURE

Companies and industries are rapidly realising the importance of sustainable development, and it is being widely adopted across a number of sectors. We believe that graphene and layered materials have the potential to take us one step closer to sustainable research and industry, ecologically friendly design and a circular economy.

These are extremely important things to consider for the development of new solutions that take advantage of flexible electronics.

The global consumption of finite materials and the amount of electronic waste we produce is ever-increasing – but novel functional materials based on graphene enable the use of environmentally compatible solvents and binders, and they are suitable for energy efficient printing processes. They could also help us achieve flexible batteries and supercapacitors with commercially viable performance, environmental-friendliness, sustainability, cost and form factor.

REFRENECES

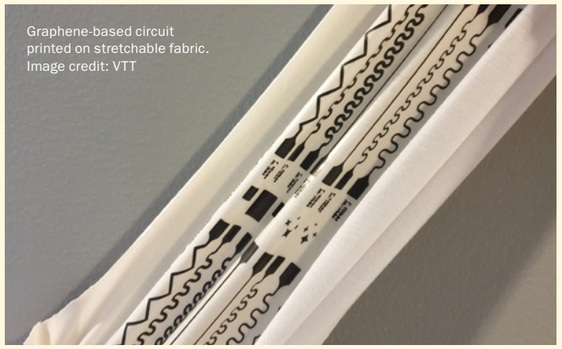
1. C. B. Huang et al., Adv. Mater., 1, 1804600 (2019)

"We worked with graphene-based photonics and electronics company Emberion to produce flexible X-ray detectors, and Nokia to produce an autonomous wearable sensing device."

Maria Smolander

Below
Memo board to store and play messages with capacitive touch capabilities. Image credit: Novalia

Bottom
Interactive board game with capacitive touch capabilities. Image credit: Novalia



Graphene-based circuit printed on stretchable fabric. Image credit: VTT

Photonics and Optoelectronics

Work Package Leader
Frank Koppens, ICFO, Spain

Work Package Deputy
Andrea C. Ferrari, University of Cambridge, United Kingdom

Using graphene and layered materials to develop photonic and optoelectronic components and integrated systems

Photonics is the science of light. It is the study of the wave and particle properties of photons, and the technology to generate, control and detect them. Optoelectronics is a sub-field of photonics, focusing on the theory, design and applications of electronic devices that interact with light.

Thanks to its unique optical and electronic properties, graphene is a rising star in the field, with many applications in solar cells, light-emitting devices, touch screens, long-range communication devices and ultrafast lasers. In the Graphene Flagship's Photonics and Optoelectronics Work Package, our mission is to use graphene and layered materials to develop components and integrated systems for applications like these.

PUTTING GRAPHENE TO THE TEST

In our Work Package, we benchmark every component against existing technologies. We only target industrial applications, and using graphene, we have a very strong potential for innovation. Photonics and optoelectronics technologies have unique advantages compared to existing technology, and the market demand is very clear.

For instance, graphene integrated with a silicon-based complementary metal–oxide–semiconductor (CMOS) circuit shows a strong advantage in terms of performance over non-silicon-based semiconductors that are not easily integrated into Si-CMOS technology. This enables much lower-cost imaging systems, such as cameras, that can detect light over a much broader range of wavelengths.

Moreover, our optoelectronic components for data communications devices require significantly less power than commercial technologies. Data transfer rates are growing exponentially over time, so our energy-efficient devices will be critical to ensure the next generation of computing is both technologically feasible and environmentally sustainable.

2019: A YEAR IN REVIEW

Our graphene-based photodetectors have now shown competitive performance across almost the entire optical spectrum: visible, infrared and terahertz. This is a fantastic achievement and it shows great potential for future developments, as these photodetectors will be further integrated with CMOS circuits on the wafer-scale to create new imaging systems and spectrometers.

We also built a flexible photodetector platform for wearable fitness monitoring,[1] and developed a coherent Raman microscope capable of producing very high-quality imaging for medical applications. Finally, our graphene-based modulators set new records with world-leading data rates of over 50 gigabits per second.

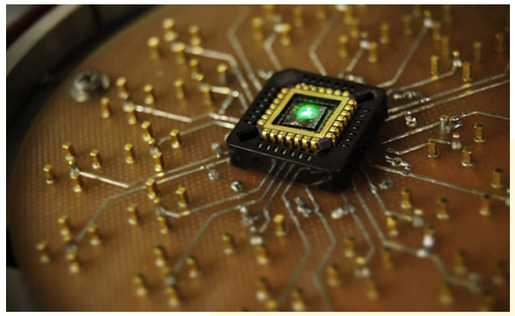
WHY THE GRAPHENE FLAGSHIP?

It has been a fascinating journey. Thanks to the Graphene Flagship, our research has evolved to the point of advanced integrated components and prototypes. Spin-off companies have already been created, such as Graphene Flagship partner Emberion and Associate Members CamGraPhIC and Cambridge Raman Imaging. It is extremely rewarding to be able to make such a direct and observable impact on society.

OUR VISION

We are targeting several prototype devices, including a radio access and datacom optical network, an integrated photonic sampling system, a plasmonic sensor integrated with an optical reader, and a graphene-enabled coherent Raman microscope. These are being developed with key industrial partners within the Photonics and Optoelectronics Work Package, such as Graphene Flagship partners Ericsson, Nokia and Thales. Over the next few years, we expect our prototypes to move up in terms of target readiness level, eventually reaching industry.

Our researchers have been key in the development of new strategies to improve power consumption, manufacturability and wafer-scale integration, showcased in papers published in Nature[2] and Nature Reviews Materials.[3] We have used this to create a roadmap for graphene-based photonics devices to surpass the technological requirements for the evolution of datacom and telecom markets driven by 5G, the Internet of Things and Industry 4.0.



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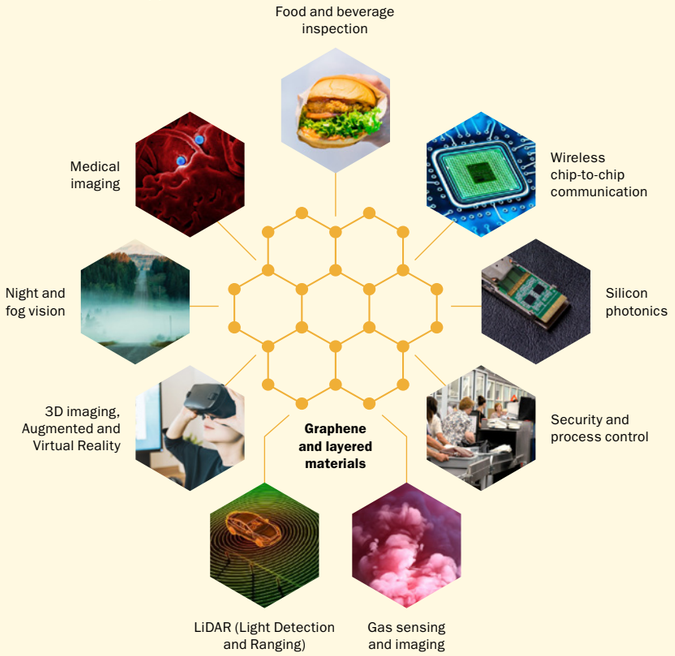
1. E. O. Polat et al., Sci. Adv., 5, p.eaaw7846 (2019)
2. D. Akinwande et al., Nature, 573, 507 (2019)
3. M. Romagnoli et al., Nat. Rev. Mater., 3, 392 (2018)

Using graphene and layered materials in photonics and optoelectronics leads to a whole host of exciting, innovative applications



Left page
Close-up photograph of a graphene-based photodetector. Image credit: ICFO

Bottom
Flexible graphene-based photodetector integrated into a wearable and transparent bracelet for fitness monitoring. Image credit: ICFO

Our research has evolved to the point of advanced integrated components and prototypes, and spin-off companies have already been created. It is extremely rewarding to be able to make such a direct and observable impact on society."

Frank Koppens

Electronic Devices

Work Package Leader
Daniel Neumaier, AMO GmbH, Germany

Work Package Deputy
Herbert Zirath, Chalmers University of Technology, Sweden

Fabricating and developing circuits and devices for the future of electronics.

We research and develop new foundations for the fabrication processes and applications of devices and integrated circuits to be used in future electronic systems. The main focus of the Electronic Devices Work Package is on wireless communications systems, logic circuits for data processing and storage, and flexible electronics.

We are particularly interested in using graphene for radio frequency devices for wireless communication, and transition metal dichalcogenindes for logic devices in programmable circuits.

Our research will have an impact on future communication technologies, which require devices that operate at higher frequencies and with a higher data transfer rate. We will drive forward new developments in quantum and neuromorphic computation.

BREAKING INTO THE FIELD

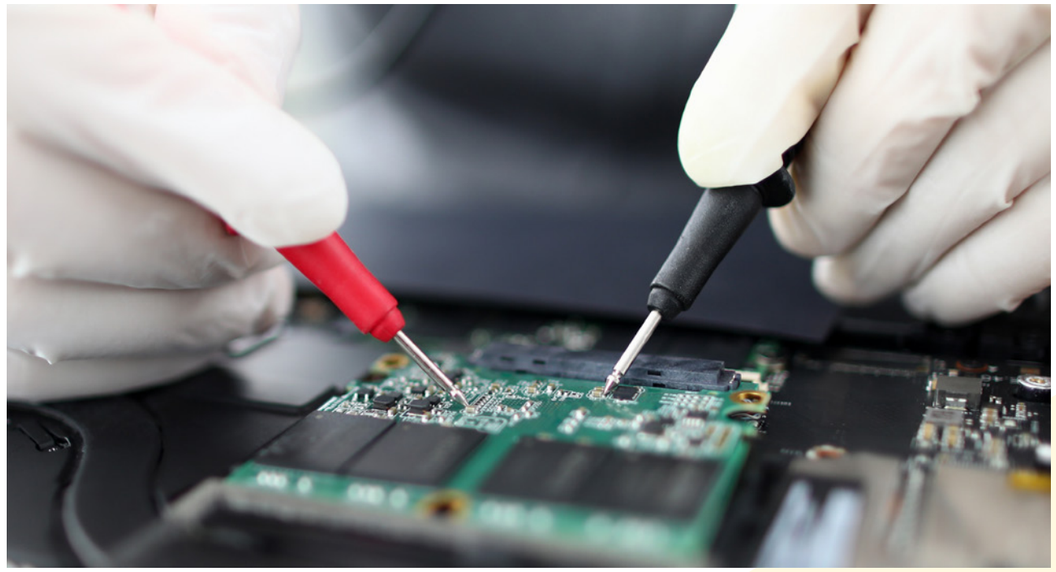
We developed several prototypes and working demonstrations that showcase the excellent performance of electronic devices based on graphene and layered materials. This includes flexible radio frequency devices circuits, new logic circuits, or receivers that operate beyond 100 GHz, which are key for new high-frequency, long-range communication technology.

We also developed solutions for critical steps in the fabrication process for electronic, photonic and sensor devices that have previously been a challenge to scientists. These have now been upscaled to be viable for manufacturing in an industrially relevant environment. For example, we developed a method to introduce low-ohmic contacts to graphene, and a method to encapsulate layers of graphene or layered materials to enable long-term stability.

2019: A YEAR IN REVIEW

In 2019, our research targeted the identification of critical parameters, like hysteresis and variation in doping levels, which are important factors to ensuring that our electronic devices are reliable and reproducible. We are also developing sustainable solutions for this.

Bottom
The Electronic Devices Work Package focuses on developing innovative electronic devices based on graphene and layered materials



This work is extremely important for us to achieve functioning applications and to develop more complex systems that involve many different devices. Our highlights from 2019 are as follows:

- Two papers in *Nature Electronics* and *2D Materials*, showing that calcium fluoride is an excellent insulator for molybdenum disulfide-based transistors, enabling ultra-low hysteresis.[1,2]
- An exploration of performance limitations in ultra-scaled electronics, such as extremely small devices, which is essential for scientists to assess the potential of layered materials for future computing applications.[3]
- A paper that shows how the unique properties of graphene can be used to fabricate a transistor based on the reflection of Dirac fermions.[4]

WORKING TOWARDS A SUSTAINABLE FUTURE

We believe that the efforts of the Electronic Devices Work Package will help to significantly reduce the environmental footprint of microelectronics manufacturing. We use graphene and other layered materials which can often replace other non-sustainable elements of device fabrication.

Furthermore, the steps to make devices using graphene and layered materials are done using thin film processes, which are highly energy and material efficient.

The next generation of electronic devices enabled by our Work Package will have lower power consumption and higher energy efficiency, which will reduce the CO_2 footprint of data centres, computers and mobile devices.

OUR VISION

We aim to achieve the system-level integration of different RF devices and components, so that we can verify the benefits for future wireless communication technology in a real system. We are also working towards proof-of-concept demonstrations of new computing concepts, for which we are expecting significant progress.

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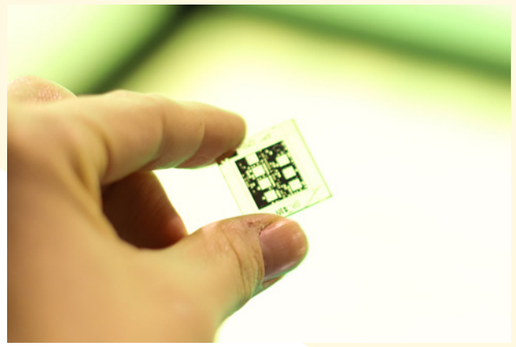
2. Y. Y. Illarionov et al., 2D Mater., 6, 045004 (2019)
3. K. A. Patel et al., 2D Mater., 7, 015018 (2020)
4. H. Graef et al., Nat. Comm., 10, 2428 (2019)

The next generation of electronic devices enabled by our Work Package will have lower power consumption and higher energy efficiency, which will reduce the CO_2 footprint of data centres, computers and mobile devices."

Daniel Neumaier

Left
Graphene can enable the development of flexible memory.
Image credit: Sophia Lloyd

Right
A small-scale electronic circuit developed by Graphenea.
Image credit: Graphenea



Graphene Is Sustainability

Supporting the United Nations Sustainable Development Goals

The Graphene Flagship's projects deliver concrete opportunities for innovation to address some of the major societal challenges in Europe. However, this effort would be meaningless without focusing heavily on sustainable development. The Graphene Flagship contributes to several UN Sustainable Development Goals (SDGs) on several different fronts and plays a role in global climate change mitigation.

SDG #3 GOOD HEALTH AND WELL-BEING
Miniaturised sensors, implants, drug delivery systems and antimicrobial coatings are all domains where graphene can play an important role. The Graphene Flagship is therefore highly involved in exploiting graphene and layered materials for biomedical applications.

To cite some examples, Graphene Flagship Associate Member Grapheal, a spin-off from CNRS-Grenoble (France), has developed a pioneering wearable and transparent graphene-based patch for the remote monitoring of chronic wounds. Another Graphene Flagship Associate Member, Atomic Mechanics, UK, devised an electronic skin prototype for applications including robotic surgery. Antonios Oikonomou, Graphene Flagship Business Developer for Flexible and Wearable Technologies, emphasises that "the booming wearables industry is eagerly looking to increase the fidelity and functionality of its offerings."

Moreover, the Graphene Flagship has a dedicated Work Package to study the possible effects of graphene and layered materials on health and the environment. By analysing the impact on bacteria, plants, animals and humans, researchers explore the biodegradability of these new materials and propose strategies to improve it.

SDG #4 QUALITY EDUCATION
The Graphene Flagship engages with graduate students all over Europe and organises annual schools for early career researchers. In 2019, the Graphene Study event in Obergurgl, Austria, covered a broad range of topics: from the fundamental science of graphene and layered materials, to their applications in electronics, spintronics and optoelectronics. During these dedicated workshops, the ratio between students and senior researchers is almost one-to-one, creating a fantastic environment that promotes direct conversations between young, promising scientists and established researchers in the field.

SDG #5 GENDER EQUALITY
Women in Graphene is a Graphene Flagship initiative to support women in all stages of their careers, encouraging networking and creating a more welcoming, gender-diverse community. Scheduled over the 2019 International Day of Women and Girls in Science, the third Women in Graphene career day was held in Manchester, UK, on 11–12 February 2019. Moreover, as in previous years, Graphene Week 2019 in Helsinki hosted a dedicated Women in Graphene session where established graphene researchers shared their experiences working up the career ladder. On top of that, in the next phase of the Graphene Flagship project, the Women in Graphene project will broaden its horizons to become a more inclusive programme: 'Diversity in Graphene', aiming to welcome a wider and even more diverse audience.

SDG #6 CLEAN WATER AND SANITATION
Graphene Flagship researchers are testing graphene in water filtration systems, as many of the existing contaminants present in Europe's water sources are resistant to conventional purification technologies. Working alongside industrial partners Medica SpA (Italy), Polymem S.A (Spain) and Icon Lifesaver (UK), all of whom are European industrial leaders in the water purification sector, the Graphene Flagship Spearhead Project GRAPHIL will produce a compact filter that can connect directly to a household sink or be used as a portable water purifying device. They estimate that their product will be commercialised by 2023.

SDG #7 AFFORDABLE AND CLEAN ENERGY
Two of the Graphene Flagship's Work Packages focus on energy generation, storage and the potential of graphene and layered materials to improve solar cells has been recognised by the Graphene Flagship since the beginning.

In 2019, a collaboration between Italian Graphene Flagship partners Italian Institute of Technology (IIT), University of Rome Tor Vergata and BeDimensional yielded a graphene-based ink that can stabilise perovskite solar cells. "Thanks to this research, we have overcome a major hurdle that stood in the way of us adopting this new technology," says Emanuel Kymakis, Graphene Flagship Work Package Deputy Leader for Energy Generation.

THE GLOBAL GOALS
For Sustainable Development

In terms of energy storage, researchers are investigating how graphene and layered materials can boost the performance of batteries and supercapacitors. "Using graphene, we have been able to increase the power of supercapacitors by a factor of five," said Paolo Bondavalli, from Graphene Flagship partner Thales Research and Technology.

SDG #8 DECENT WORK AND ECONOMIC GROWTH
SDG #9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
The Graphene Flagship aims to bring graphene and layered materials out of academic laboratories and into society in the form of new products, investments and employment opportunities. To do this, the Graphene Flagship attracts investment and catalyses the development of new commercial enterprises. For example, InBrain Neuroelectronics, a new spin-off company from ICN2 in Spain, developed graphene-enabled retinal implants that can provide artificial vision to patients with retinal degeneration, attracting significant investment from an external funder. For further information on successful Graphene Flagship spin-offs, take a look at our special feature on page 18.

SDG #11 SUSTAINABLE CITIES AND COMMUNITIES
SDG #13 CLIMATE ACTION
Graphene can be incorporated into existing pollution removal and monitoring technologies to significantly improve their performance, such as in the removal of pollutant gases like nitrogen oxides from the atmosphere.

In 2019, nine Graphene Flagship partners[1] developed a graphene-titania photocatalyst that degrades up to 70% more atmospheric nitrogen oxides than standard titania nanoparticles in tests on real pollutants. "We answered the Graphene Flagship's call and decided to couple graphene with the most-used photocatalyst, titania, to boost its photocatalytic action," comments Marco Goisis, research coordinator at Graphene Flagship partner Italcementi.

In addition, a further five Graphene Flagship partners[2] created a low-cost, low-energy-consuming NO_2 sensor that measures the level of this gas in real-time and could help to visualise pollution in urban areas. NO_2 gas is produced by burning fossil fuels, and it can cause airway inflammation, leading to breathing problems and even asthma attacks. For this reason, the European Union has introduced legislation to regulate the amount of NO_2 in the air. The Graphene Flagship's new NO_2 sensor could prove to be a crucial development.

SDG #12 RESPONSIBLE CONSUMPTION AND PRODUCTION
Graphene has the potential to enhance the performance of different materials and alleviate their carbon footprint. For example, graphene composites can be used to make lighter packaging, reducing costs and energy consumption. EU-based packaging and processing company Tetra Pak joined the Graphene Flagship in 2019 as a new Associate Member, with the goal of enabling new functionalities and increasing recyclability.

SDG #17 PARTNERSHIPS FOR THE GOALS
The Graphene Flagship nourishes partnerships and collaborations between its nearly 150 academic and industrial partners, and within its extensive network of Associate Members, active in Europe and the global scene. For more information on the importance and impact of collaborations enabled by the Graphene Flagship, please see our special feature on page 48.

NOTES
1. University of Bologna, Politecnico di Milano, CNR, NEST, Italcementi, Italy; HeidelbergCement Group, Germany; the Israel Institute of Technology, Israel; Eindhoven University of Technology, the Netherlands; and the University of Cambridge, UK.
2. National Physical Laboratory, UK; Chalmers University of Technology, Sweden; alongside colleagues at the Advanced Institute of Technology, UK, Royal Holloway University, UK, and Linköping University, Sweden.

Sensors

Work Package Leader
Peter Steeneken, TU Delft, The Netherlands

Work Package Deputy
Sanna Arpiainen, VTT, Finland

Using graphene and layered materials to develop and improve physical and biological sensing devices

The flexibility and electrical conductivity of graphene offers a very high level of sensitivity. In the Sensors Work Package, we exploit the unique properties of graphene and other layered materials to develop new sensing materials and devices. Our main goal is to make sensors that are smaller and more sensitive than existing ones.

We also want to develop new optical readout methods, integrate sensors into electronic devices and even into packaging, and design new ways to fabricate them.

2019: A YEAR IN REVIEW

2019 was a great year for graphene-based sensors. We showcased four new developments at Mobile World Congress last year: pressure, gas, touch and magnetic field sensors.

We constructed an innovative piezoresistive pressure sensor based on platinum diselenide, with record-breaking performance, as well as a capacitive pressure sensor which outperforms the best commercial micro-electromechanical pressure sensors: miniature machines with both electrical and mechanical components. We also developed new biosensors to detect DNA and vitamin B12, which could be adopted in biomedical research and diagnosis.

MAKING A REAL IMPACT ON THE WORLD

One of our proudest developments is a presence detector for home protection, using a graphene pressure sensor chip with a capacitive readout circuit. The membrane has 10,000 sensors, and a disturbance of just a few electrons in the membrane can detect the opening of a door.

We also produced an ‘electronic nose’ – a gas sensor for home and workplace safety which can detect toxic gases with very fast response times, using an intricate micro-electromechanical microheater platform.

We sense our future is bright. Our research enables smaller sensors with better performance in terms of sensitivity and detection limits, which allow for smaller quantities to be measured. Smaller detection limits also mean faster response times, which is crucial for sensors that detect diseases or toxins.

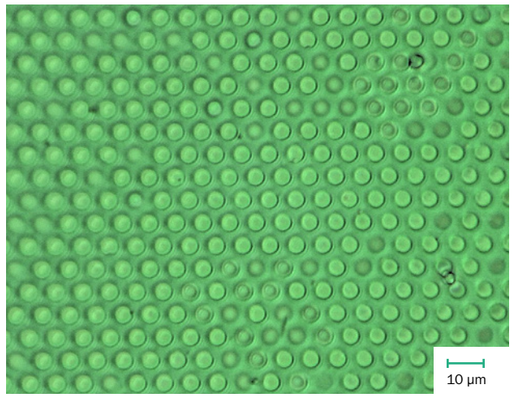
We also apply this technology to climate control and pollution monitoring, and we are working on integrating graphene sensors into mobile devices and autonomous sensor nodes for more widespread availability.

BREAKING INTO INDUSTRY

In order to bring graphene-based sensors onto an industrial scale, we need to develop graphene sensors that are compatible with complementary metal-oxide-semiconductor (CMOS) technology, which is commonplace in computer circuit chips, microprocessors and memory chips.

In 2019, we demonstrated several pressure sensors, magnetic field sensors, microphones, gas sensors and biosensors that can be operated and read-out using conventional printed CMOS-integrated circuits.

We aim to turn the Graphene Flagship’s goal of industrialisation into a reality by collaborating closely with EU-based companies, including Graphene Flagship partners Prognomics and Infineon. We have already shown the first proof that our graphene sensors can be integrated into CMOS chips on a commercial basis, so it is only a matter of time before we can produce graphene-based sensors on an industrial level.



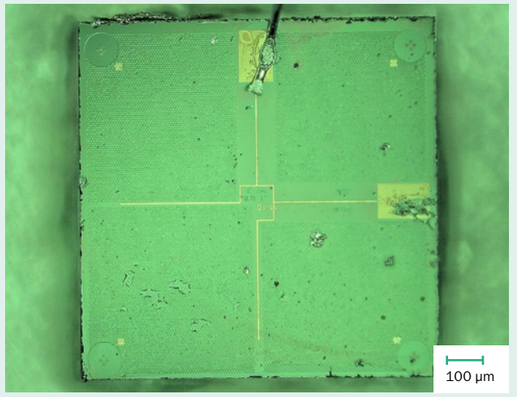
Above
An array of graphene pressure sensor membranes, each 5 micrometers in diameter. Image credit: TU Delft/ Peter Steeneken et al.

WORKING TOWARDS A SUSTAINABLE FUTURE

We can use our graphene ‘electronic nose’ and gas sensors to monitor concentrations of pollutants in the atmosphere. If we can integrate these sensors into mobile phones on a large scale, we can increase awareness and obtain high-resolution data on pollution in urban environments, which would help governments to identify and monitor pollution and sources of air contamination and decide on preventative measures.

Furthermore, our graphene biosensors can be functionalised and integrated with water supply and exhaust systems to monitor water quality in a similar manner.

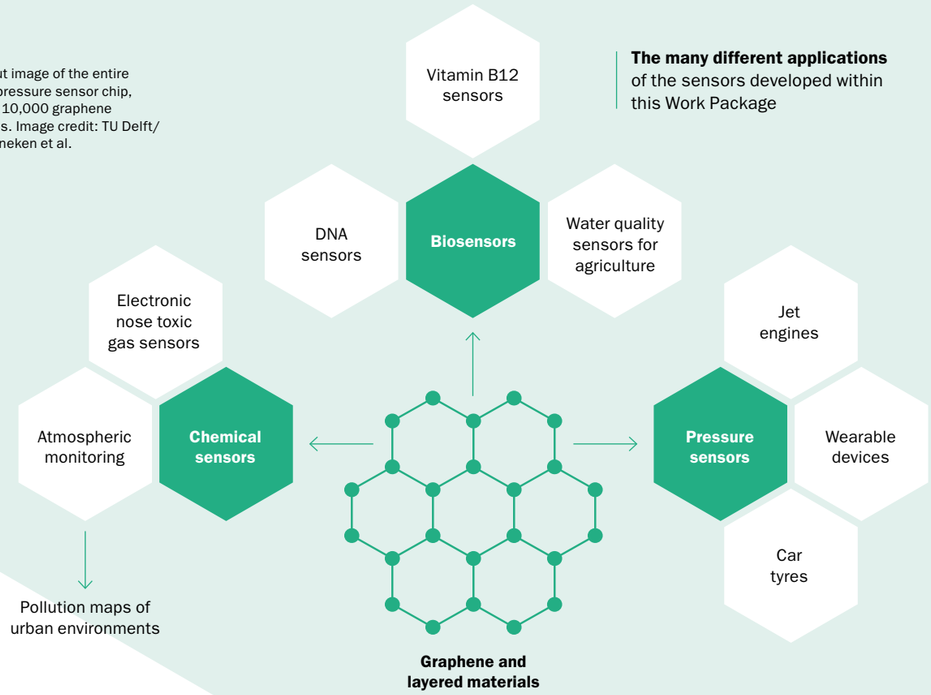
They can also be applied to the agriculture and food sector, by creating low-power wireless networks of graphene sensors to precisely monitor the growth conditions of crops, such as pressure, temperature, humidity and gas composition. Farmers can then use this information to improve crop yields, reduce energy usage and ensure the crops receive sufficient nutrients and clean water.



Above
Zoomed out image of the entire graphene pressure sensor chip, containing 10,000 graphene membranes. Image credit: TU Delft/ Peter Steeneken et al.

The Graphene Flagship provides a targeted research platform with a vast network for continuous collaboration with world leading groups in graphene research. And by working together, we achieve more.”

Peter Steeneken



The many different applications of the sensors developed within this Work Package

Biomedical Technologies

Work Package Leader
Kostas Kostarelos, University of Manchester, United Kingdom

Work Package Deputy
Jose Garrido, ICN2, Spain

Designing graphene-enabled technology for diagnosis, medical monitoring and treatment

In the Biomedical Technologies Work Package, we take advantage of the unique properties of graphene, such as its ability to interact with electro-active cells and tissues in the body, for medical monitoring, diagnosis and neuropathic therapy.

The graphene-based neural interface devices developed in our Work Package offer the capability to record brain activity, allowing neuroscientists and clinicians to access previously untapped bandwidths of electrophysiological signals in serious brain disorders, such as epilepsy. We aim to translate this technology into graphene-based products in the biomedical field, enabled by our industrial partners.

We are hopeful that our research will allow other scientists around the world to use graphene to better understand neural signaling and physiology at the pre-clinical level, and in parallel, offer clinicians and patients improved treatment options for blindness, epilepsy and other neurological diseases.

NEW HORIZONS IN NEUROLOGICAL DIAGNOSIS

Neurological diseases like epilepsy and Parkinson's disease are currently not well-understood, and they affect millions of people worldwide. For many of these patients, the treatment options available are limited – but the graphene technologies we develop have the potential to change the way we diagnose, treat and monitor these diseases.

Our Work Package will organise and execute a clinical study in the next phase of the project using graphene-based electrodes. They allow for the wireless recording of neurons and brain activity for the diagnosis of diseases of the brain. This will be the first in-human trial of a graphene-based medical device, and we believe the findings of this study will open up new avenues for graphene to be translated into a clinical environment.

WORKING WITH KEY PLAYERS IN INDUSTRY

We have a number of industrial partners who are excited to join us in taking advantage of graphene's properties for brain recording and stimulation.

We worked with Graphene Flagship partner MultiChannel Systems, based in Germany, on our graphene-based neural interfacing electrodes for experimental neuroscience. Furthermore, Graphene Flagship partner Guger, based in Austria, created hardware to process electrophysiological data recorded using field-effect transistor technology. Both of these partners aim to make these products available to consumers in 2020.

2019: A YEAR IN REVIEW

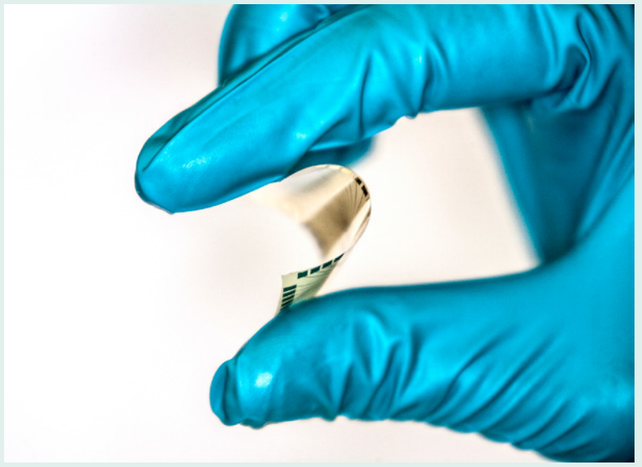
We were very pleased to collaborate with Nature Nanotechnology to run a workshop during Graphene Week 2019: The Science and Science Fiction of Nano-neuro Interfaces. We combined this with a number of public engagement and outreach opportunities to discuss graphene and layered materials with the wider public.

Furthermore, scientists from our Work Package pioneered graphene-enabled retinal implants to provide artificial vision to patients with retinal degeneration. The success of this project has attracted investments and awards from external agencies and has also prompted the creation of a spin-off company, InBrain Neuroelectronics, who will commercialise the technology and guide its transition into the biomedical sector.

OUR VISION

We anticipate that graphene-based devices for pre-clinical use will be on the market in the next three years, and we aim to have a working device approved for human use within five years.

We are also very conscious of the need for continual basic research on graphene to continue. We believe that the biological properties of graphene have great potential, and that they must be further understood before we can fully harness them in biomedical applications. While graphene-based technology for diagnosis has come a long way, our main goal for the next phase of the project is to get graphene-based treatments for neurological diseases to the pre-clinical stage within the next few years.



Above
Flexible neural interface device developed by our spin-off company. Image credit: InBrain Neuro-electronics

Left page
Smart bandage with built-in biosensor for at-home healing monitoring using a smartphone app. Image credit: Grapheal

Bottom
Neural interface device to record neuron activity. Image credit: ICN2

The graphene-based neural interface devices developed in our Work Package offer the unprecedented capability to record brain activity, allowing neuroscientists and clinicians to diagnose serious brain disorders."

Kostas Kostarelos

Health and Environment

Work Package Leader
Maurizio Prato, University of Trieste, Italy

Work Package Deputy
Alberto Bianco, CNRS, France

Profiling graphene's biosafety and setting standards for its safe use in research and industry

In the Graphene Flagship's Health and Environment Work Package, we assess the safety profile of graphene and layered materials and define protocols for their safer use.

We start by looking at the physicochemical properties and bio-nano interactions of graphene and layered materials when they are introduced to biosystems, considering all routes of exposure. We believe that three fundamental steps are necessary for the safety profiles of graphene and layered materials to be fully characterised:

- Maximise the synergy and coordination between different research strategies.
- Monitor toxicity at different levels: cellular, organ, tissue and environmental.
- Define protocols for the materials' safer use, where necessary.

SAFETY FIRST

Graphene and layered materials are rapidly approaching working applications in many areas: electronics, optoelectronics, photonics, energy, materials and composites, and biomedicine, just to cite a few. For these new materials to be viable for industrial and clinical applications, it is fundamental to fully understand their impact on health and the environment.

We still have gaps to fill in risk-related knowledge, and this is what drives us. It is therefore crucial to develop a thorough and reliable safety profile of graphene and layered materials and offer solutions if any risks are identified.

In the EU, all manufactured materials and nanomaterials must follow REACH regulations, established by the European Chemicals Agency, in order to be authorised for industrial production and commercialisation. In 2020, our Work Package will work with the European Chemicals Agency to develop and implement the official guidelines for the safety assessment of graphene and layered materials.

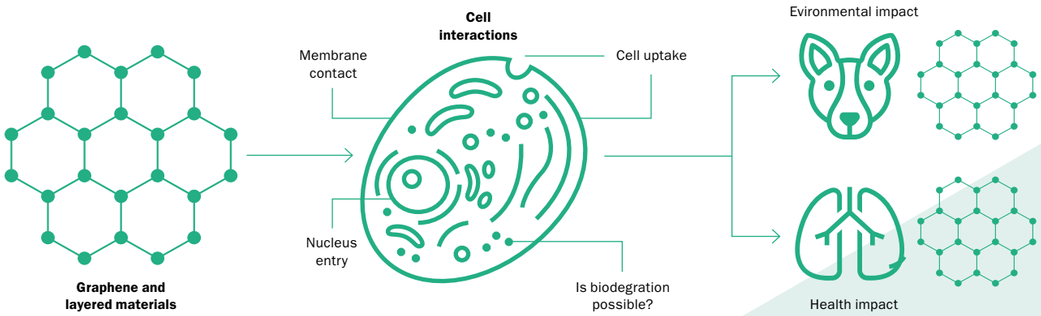
2019: A YEAR IN REVIEW

We studied the degradability of graphene and layered materials, and designed a graphene oxide conjugate, with increased biodegradability, that can stimulate neutrophils to secrete myeloperoxidase: the human peroxidase that degrades unwanted molecules, materials and microorganisms in the lungs.[1]

We investigated ways to revert hyperexcitability, which is one of the causes of epilepsy and other similar conditions, using small-size graphene oxide. In the future, this material could play a neuroprotective role in the treatment of brain-related diseases.[2]

We also looked at the effects of graphene oxide on a microcosm consisting of algae and bacteria as primary producers, chronomid larvae as primary consumers and decomposers, and larvae of the Iberian ribbed newt as secondary consumers. We fully characterised the toxicological effects of graphene oxide on the system and reported genotoxicity in the top predators and significant effects on communities in the sediment.[3]

Graphene and layered materials could interact with cells in different ways, and this may have consequences for the world around us



Studies like these, which are the focal point of our Work Package, are extremely important for scientists to fully understand the biological and environmental safety of graphene and layered materials.

WHY IS THE GRAPHENE FLAGSHIP IMPORTANT TO US?

The Graphene Flagship provides a fantastic opportunity to explore new fields of technology with the potential to cause a deep impact on the future and quality of life of humankind. This unique framework makes it possible to unite and merge the strength and expertise of researchers with very different scientific backgrounds, and it brings together cutting-edge fundamental and applied research, helping to bridge the gap between academia and industry.

The Health and Environment Work Package is a network of scientists who all share a common aim: ensuring the safety of graphene and layered materials. Our work in harmony with the Graphene Flagship enabled us to produce two extremely important publications on graphene classification and safety,[4,5] which will be critical to the field for years to come.

WORKING TOWARDS A SUSTAINABLE FUTURE

As scientists, we have a responsibility to work consciously towards an environmentally friendly and sustainable future. For both research and industry involving graphene and layered materials, we must achieve this by developing an exhaustive understanding of all possible interactions with human health and our ecosystem.

Only by fully understanding all of the properties of these novel materials, including any potential impacts on health and the environment, will we be able to overcome any risk at any point in the research and production chain. This is the principal goal of our Work Package.

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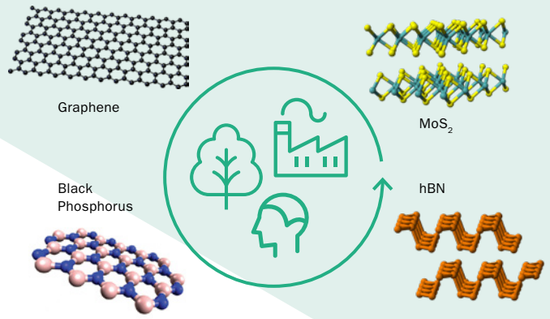
4. P. Wick et al., Angew. Chem. Int. Ed., 53, 7714 (2014)
5. B. Fadeel et al., ACS Nano, 12, 10582 (2018)

The effects of graphene and layered materials on health and the environment must all be fully characterised



> Only by fully understanding all of the properties of these novel materials, including any potential impacts on health and the environment, will we be able to overcome any risk at any point in the research and production chain."
>
> Maurizio Prato

Bottom
Could the Graphene Flagship help to mitigate pollution in urban environments?

Collaboration Breeds Success

Collaboration is at the heart of the Graphene Flagship. Top level researchers in academia, research and industry across Europe are encouraged to discuss strategies that will push graphene to the market.

“The Graphene Flagship is one of the largest collaborative research projects ever organised by the European Commission. We bring together about a thousand researchers from different backgrounds, working side-by-side on common projects. This collaborative ecosystem is what makes the Graphene Flagship a huge success,” says Jari Kinaret, Graphene Flagship Director.

Here are just a few examples among the countless collaborations successfully established this year within the Graphene Flagship.

COLLABORATION FOR KNOWLEDGE

In 2019, the Graphene Flagship produced a comprehensive guide that condenses the knowledge of graphene production and processing acquired and developed by the Graphene Flagship over the past six years. Co-authored by 70 international experts and incorporating over 1,500 references, this open access review will benefit 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. “For scientists looking to study graphene and layered materials, or companies that want to mass produce them, this knowledge is vital,” explains Mar García-Hernández, Graphene Flagship Work Package Leader for Enabling Materials and coordinator of this comprehensive review. This publication will certainly become the ultimate manual in the field of graphene production – just a month after its release, the 500-page paper had already been downloaded over 17,000 times!

COLLABORATION FOR INNOVATION

The Graphene Flagship also started a successful collaboration to push graphene-enabled batteries towards commercialisation. Graphene Flagship partner Italian Institute of Technology (IIT) worked alongside its spin-off company BeDimensional, now a Graphene Flagship Associate Member, and the established industrial manufacturer VARTA Micro Innovation GmbH, to stabilise silicon-lithium batteries using graphene. Graphene enables higher battery capacities that could be used in a variety of small electronic gadgets, from watches and wearable devices to car keys and wireless headphones. Kari Hjelt, Head of Innovation of the Graphene Flagship, insists: “This successful collaboration between Graphene Flagship partners exemplifies the importance of the systematic support by the European Commission for high-tech innovations. It also highlights how Graphene Flagship Spearhead Projects can greatly help in our quest to move materials out of the research labs and into real components and products.”

Another example of successful academic–industrial collaboration nurtured within the Graphene Flagship is in the field of graphene-enabled composites. A multidisciplinary team of researchers from academic institutions, commercial enterprises and world leading aerospace and automotive industries demonstrated the potential of integrating graphene and layered materials into composites for aircrafts and vehicles, making them lighter, which could potentially reduce CO_2 emissions. Researchers at nine partner universities[1] joined forces with scientists at our partner companies Nanesa, based in Italy, and Avanzare, based in Spain, to review the technological viability of the composites. “Thanks to the Graphene Flagship, we could create many different prototypes to test properties such as flame retardancy, water absorption, electrical and thermal conductivity, and electromagnetic interference shielding,” says Francesco Bertocchi, President of Nanesa and co-author of the paper.

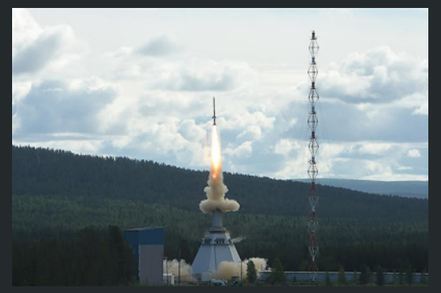
Finally, our partners Airbus and Fiat-Chrysler Automobiles evaluated the impact of these prototypes on the aerospace and automotive industries – both key for the European economy – and assessed their commercial viability. “The Graphene Flagship provides a stable, clear, long-lasting partnership for different partners to work together,” comments Vincenzo Palermo, Graphene Flagship Vice-Director and lead author of the paper.

COLLABORATION FOR NETWORKS

Throughout the year, the Graphene Flagship Innovation Team hosted multiple Graphene Connect events to reach out to new potential partners and facilitate connections. Among them, the Graphene Connect & Health Investment Forum, held on November 6, 2019 in Barcelona, Spain, brought together academic experts in graphene, as well as investors and business leaders from the healthcare and medical sectors. The Graphene Flagship and COMB, in collaboration with ICN2, organised this event to showcase graphene-enabled innovative projects and prototypes targeting the healthcare sector. Moreover, Cinzia Spinato, Graphene Flagship Business Developer at ICN2, and Nadia Pons, Head of Innovation at COMB, agree that for the first time, Graphene Connect gave entrepreneurs in the field the opportunity to pitch their ideas directly to investors.

Also in the biomedical sector, a collaboration between Graphene Flagship partners[2] facilitated the development of a new graphene-enabled implant to map low frequency signals in the brain. This technology paves the way for the next generation of brain-computer interfaces offering crucial information about the onset and progression of epileptic seizures and strokes. This technology was patented by ICN2, and the images were captured thanks to a technique developed by the researchers at ICFO. The prototype was adapted for brain recordings thanks to external collaboration with the biomedical research institute August Pi i Sunyer (IDIBAPS), demonstrating that synergistic collaboration can yield fruitful, clear-cut results.

Finally, yet another rewarding collaboration enabled by the Graphene Flagship sent graphene into space. The Materials Science Experiment Rocket (MASER) 14 was launched on 24 June 2019 from the European Space Centre in Esrange, Sweden, thanks to a collaboration between the European Space Agency (ESA), the Swedish Space Corporation (SSC), and three Graphene Flagship partners.[3] Studying the self-assembly of graphene flakes in a zero-gravity environment helps us to further understand graphene’s fundamental properties, granting us insight into the methods and mechanisms of graphene printing on Earth. Moreover, these experiments are the first step towards graphene printing being available for long-term space exploration. Graphene-based composites for radiation shielding purposes are an essential requirement of manned space exploration.



Top
New composites for automotive and aeronautic applications developed by Graphene Flagship researchers were tested by industry partners.

Left
The MASER 14 rocket sent graphene into space. Image credit: Christophe Minetti, ULB

NOTES

1. Queen Mary University and National Graphene Institute, UK; FORTH-Hellas and University of Patras, Greece; CNR, University of Turin, University of Trento and KET-LAB, Italy; Chalmers University of Technology, Sweden.
2. Barcelona Microelectronics Institute (IMB-CNM, CSIC), Catalan Institute of Nanoscience and Nanotechnology (ICN2), and ICFO – all based in Barcelona, Spain.
3. Université Libre de Bruxelles, Belgium; University of Pisa, Italy; and the University of Cambridge, UK

GRAPHENE FLAGSHIP ANNUAL REPORT 2019

Enabling Materials

Work Package Leader
Mar García-Hernández, CSIC, Spain

Work Package Deputy
Jonathan Coleman, Trinity College Dublin, Ireland

Developing scalable synthesis methods for graphene and layered materials

Our mission is to develop scalable methods to prepare graphene and other layered materials, and their heterostructures. We also provide state-of-the-art material samples for other Work Packages within the Graphene Flagship, enabling them to perform new experiments and build new devices using the very best materials available.

NEW ROUTES TO HIGH-QUALITY GRAPHENE

In order to incorporate graphene and layered materials into working applications and get them on the market, we need protocols to produce them on a large scale with high quality.

In the Enabling Materials Work Package, we work from an a priori perspective, proposing new cost-efficient, reliable and reproducible production methods based on theoretical deduction and careful planning. Our fundamental efforts allow us to support scientists at the Graphene Flagship, enabling their research and helping them to get the best out of graphene and layered materials.

Our Work Package coordinated the creation of the Graphene Flagship handbook for graphene production, recently published in the scientific journal *2D Materials*. This comprehensive publication encompasses more than 1,500 references and the knowledge of 70 co-authors from Graphene Flagship partners and Associate Members.[1] It details techniques to produce and process graphene and layered materials, in addition to describing the key characterisation procedures. Only one month after publication, it had already been downloaded over 17,000 times.

2019: A YEAR IN REVIEW

We achieved the growth of boron nitride on various different substrates. This will allow us to construct heterostructures that meet the requirements for graphene incorporation into a variety of different optoelectronics applications, such as receivers for data transfer.

We also mastered the growth of transition metal dichalcogenide (TMD) monolayers, a family of layered materials with complementary properties to graphene. Monolayer TMDs, such as tungsten disulfide, have a direct band gap, meaning they can be used as transistors in electronics and as emitters and detectors in optics.

Furthermore, we devised a new platform for the clean functionalisation of graphene and layered materials for applications in biorecognition. This is used to detect extremely low concentrations of proteins.

Thanks to the Graphene Flagship, 2019 was a great year for us, and we are looking forward to many great years to come.

THE IMPORTANCE OF SUSTAINABILITY

It is crucial to bear in mind the availability of raw materials when designing new processes and applications. One focus of the Graphene Flagship is on the miniaturisation of devices: finding ways to produce devices based on graphene and layered materials using the smallest possible quantity of starting material.

Our Work Package contributes to this effort by synthesising the thinnest ever reported set of materials – from conductors to insulators to polymers – and by using them to construct new, exciting heterostructures with great potential.

Bottom
It is crucial to bear in mind the availability of raw materials when designing new processes and applications. Image credit: Alexandra Csuport

Right page
We need protocols to produce high quality graphene and layered materials on a large scale. Image credit: Graphenea

PAVING THE WAY TO AN INDUSTRIAL FUTURE

We have developed a large number of optical characterisation methods to assess the properties of our materials, such as the number of layers, as they are grown in real time.

Evaluating important factors – like the surface uniformity, doping level and thickness of graphene and layered materials – over the course of the growth process, is extremely valuable: it helps researchers to ensure they obtain materials of the highest possible quality, with a desirable set of properties for application. For this reason, our characterisation methods may also help to bridge the gap between research and industry.

We also collaborated with the International Electrotechnical Commission (IEC), and we were deeply involved in the planning and organisation of the 2019 Spring IEC/TC 113 committee meeting. The meeting focused on the standardisation of graphene and layered materials in research and industry, and we created a set of agreed-upon definitions to classify different grades of graphene and layered materials.

This provides a safety net for the commercialisation of these materials, so that potential buyers know exactly what they are getting. This is a crucial step towards getting graphene and layered materials into industry and onto the market.

Over the next few years, we will continue to work on the large-scale synthesis of functional heterostructures for a broad range of applications.

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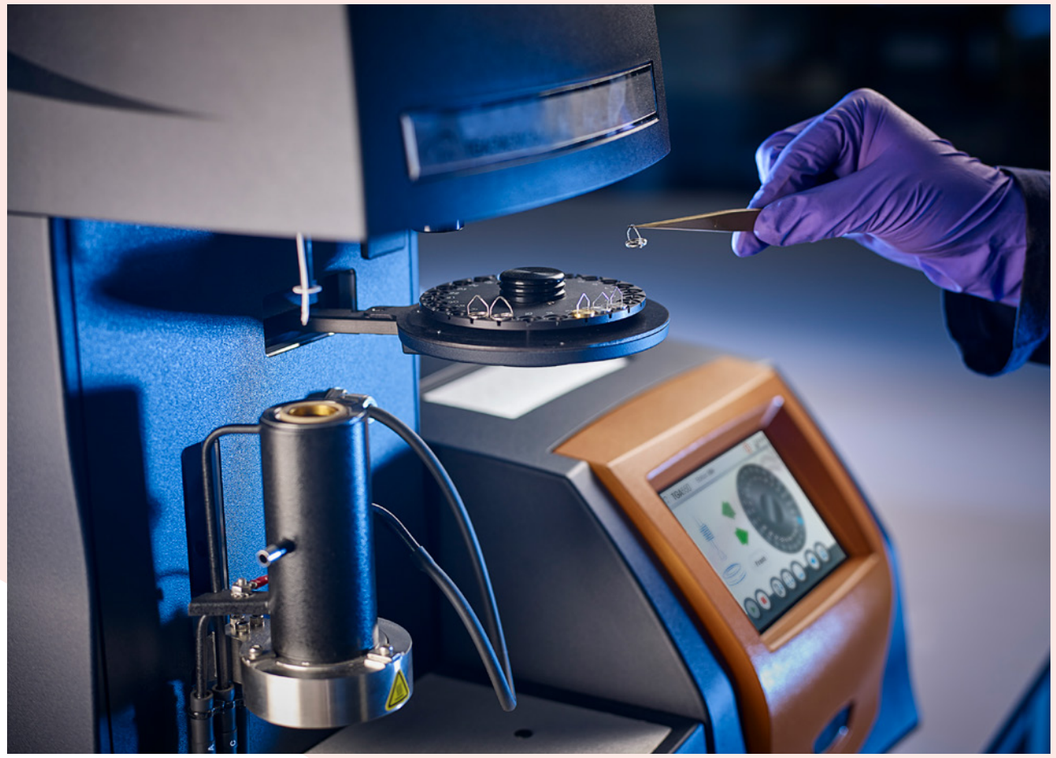
Our fundamental efforts allow us to support scientists at the Graphene Flagship, enabling their research and helping them to get the best out of graphene and layered materials.”

Mar García-Hernández



Spintronics

Work Package Leader
Kevin Garello, IMEC, Belgium

Work Package Deputy
Stephan Roche, ICN2, Spain

Exploring graphene's potential in spintronics applications for data transfer, processing and storage

The mission of the Graphene Flagship's Spintronics Work Package is to explore the potential of graphene and layered materials for applications in spintronics: the transfer, processing and storage of information based on the spin degree of freedom of electrons in the material.

Our first objective is to determine how to improve the performance of magnetic tunnel junctions: two layers of metallic material that allow electrons to pass between them when a voltage is applied, enabling data transfer, using a combination of magnetic materials and graphene and layered materials. This is crucial for the development of new magnetic random-access memory (RAM) technology for data storage and computer processing.

Our second objective is to find the upper limit for spin-to-charge conversion mechanisms, such as the spin Hall effect, to generate pure spin currents in graphene. Harnessing the potential of this phenomenon could lead to a new wave of enhanced magnetic RAM devices and open the door to ultra-low energy consumption computing, meaning that our data centres, mobile devices and interconnected electronics could become more sustainable and significantly cheaper to power.

Furthermore, we are continually evaluating the potential of new and emerging layered materials to further advance ultra-compact spin-based technologies.

BREAKING INTO THE FIELD

Spintronics fosters the emergence of new markets across a broad range of fields. Aside from magnetic RAM technology, spintronics could play a crucial role in the development of new technology for motion sensing, mechanical engineering, computer games, robotics, fuel sensors, speed control, navigation systems and even minimally invasive surgery.

Efficient spintronic devices have huge advantages over traditional electronic components: they have low volatility, low power consumption and density, and high data transfer speed. All of these properties are essential for the Internet of Things and for the future of high-performance computing. In the Spintronics Work Package, we take advantage of these unique properties to develop novel and diverse technologies based on graphene and layered materials.

2019: A YEAR IN REVIEW

We experimentally demonstrated spin-to-charge conversion mechanisms in graphene using spin precession and non-local measurements. Not only did we demonstrate the spin-related character of the signals, but we also quantified their efficiencies, which were the best ever reported for any material at room temperature. These efficiencies can even be tailored using electrostatic gating, which makes them extremely useful for the electrical manipulation of spin information, for applications in spintronics-based data storage.[1,2]

We also found that graphene can be made magnetic when placed in proximity to a layered insulating magnetic material in a heterostructure, formed by assembling graphene with a layered ferromagnetic insulator.[3] This could help us to utilise proximity-induced magnetic interactions and spin-polarised filters in layered material-based heterostructures, which could form the basis for future research in spintronics and topological quantum technologies.

WORKING WITH KEY PLAYERS IN INDUSTRY

Stemming from our efforts, fundamental spin-to-charge conversion mechanisms, such as spin-orbit torque (SOT), were discovered and patented in Europe. This technology was incorporated into high-technology readiness level developments, such as the large-scale integration of SOT-magnetic RAM by Graphene Flagship partner IMEC. Our European partners are actively collaborating within the Spintronics Work Package with the aim of assessing and accelerating the integration of graphene and layered materials into European spintronics research.

From the inception of our Work Package, we have worked closely with a European SME, Graphene Flagship partner NanOsc AB, to develop nano-oscillators for high-speed communication technologies. Furthermore, we collaborated with Graphene Flagship partner IMEC to tackle the integration of magnetic memories with layered materials, one of the biggest challenges in spintronics. Going forward, we will be working with Graphene Flagship partner Graphenea, and other EU-based enterprises such as Singulus Technologies, to extend our connection to industry and advance the technology readiness levels of our products.

OUR VISION

Over the next few years, we want to co-integrate the current family of layered materials used for magnetic tunneling junctions – graphene, hexagonal boron nitride and transition metal dichalcogenides – with newly discovered layered materials to further enlarge the portfolio of powerful, low-energy-consuming spintronics materials.

We will focus on improving the performance of magnetic tunnel junctions to allow us to provide industry-compatible solutions for the growth of layered magnetic RAM materials. These materials will be supported by the Graphene Flagship to accelerate the co-integration of wafer-scale layered materials with magnetic compounds, which will enable our spintronics materials to find more applications in wafer-scale computer chip fabrication.

Spintronics is currently at a pre-industrial stage, so we are focusing on outperforming the previous record numbers for magnetic RAM technology in terms of density, writing speed and energy consumption. This will serve as a pathfinder for scientists to prepare industry-compatible building blocks for future industrial-scale spintronics applications.

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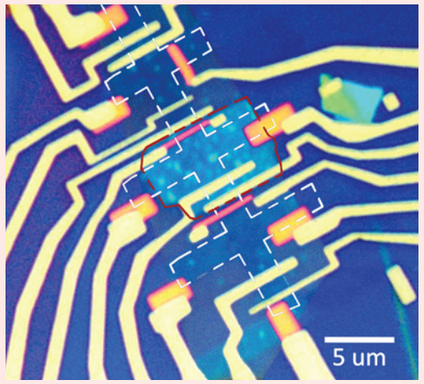
The Spintronics Work Package aims to exploit the performance of layered material-enhanced memory technology, with the ultimate goal of enabling large-scale co-integration of these materials in an industrial environment."

Kevin Garello



Left page
Graphene and layered material-based spintronics can enhance data storage technologies

Above
Micro-sized spintronic magnetic memory chip, created by interfacing graphene with layers of transition metal dichalcogenides.
Image credit: ICN2

Bottom
An array of data storage devices

GRAPHENE FLAGSHIP ANNUAL REPORT 2019

Enabling Research

Work Package Leader
Vladimir Fal'ko, University of Manchester, United Kingdom

Work Package Deputy
Alberto Morpurgo, University of Geneva, Switzerland

Exploratory studies of graphene and layered materials leading to new concepts and applications

Our principal goal is to explore new avenues in fundamental research on graphene and layered materials. Our research allows us to conceptualise new ideas for the uses of these materials, and to find new ways of translating fundamental knowledge to applications in European industry.

We also explore the potential of graphene and layered materials to enable new functionalities in electronics, photonics and other technologies, collaborating with other Work Packages in the Graphene Flagship to investigate new materials and improve the devices and technologies developed at our partner institutions.

FUNDAMENTAL RESEARCH

We conduct our research at the most fundamental level to build up our scientific knowledge and expand the applications of graphene and layered materials. Our findings help other Work Packages to further advance their research and have even enabled us to create new start-up companies: Graphene Lighting, Graphene Security and Eksagon, an Associate Member of the Graphene Flagship.

We primarily focus on the following aspects of fundamental research:

- Characterising the structural, optical, electronic and thermal transport properties, modelling the interactions and searching for new applications of graphene, hexagonal boron nitride (hBN) and transition metal dichalcogenides (TMDs).
- Developing and characterising new 'sandwiched' heterostructures of layered materials and performing exploratory studies into new layered crystals and heterostructures.
- Investigating the effects of intercalating metals, ionic liquids, and electrolytes in graphene and other layered materials to control material properties and create new functionalities.
- Designing new electronic and optoelectronic devices based on encapsulated heterostructures based on ultra-high-quality graphene, TMDs and other layered materials.

2019: A YEAR IN REVIEW

We published over 10 papers in internationally renowned peer-reviewed journals, including Nature Materials, Nature Physics, Nature Communications and Nano Letters, further elucidating the properties of graphene and layered materials and providing a foundation for future research by all Work Packages in the Graphene Flagship. We also developed new layered materials that emit light in any colour of the spectrum.[1]

LIGHTING THE WAY

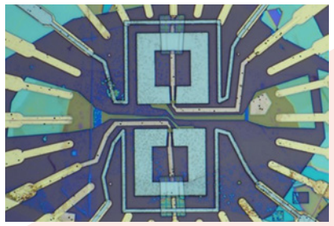
Finding new light-emitting semiconductors is essential for developing many electronic devices, and even more so if we can create artificial structures with properties tailored towards the needs of specific applications.

We achieved our tailorable light-emitting materials by combining indium selenide films with layers of TMDs, such as molybdenum diselenide. Light emission occurs when electrons and holes recombine at the band edges, resulting in an optical transition. These heterostructures have great potential to be used in future applications on an industrial level, as they can be used to make light emitting devices – such as LEDs – with simple fabrication methods.

THE FIRST STEP TOWARDS NEW APPLICATIONS

We apply our scientific knowledge to the design and manufacture of new electronic and optoelectronic devices. This includes the following:

- Electrostatically controlled circuits using quantum dots and wires based on hBN-encapsulated layered materials for quantum information processing.
- Graphene-superconductor hybrids and two-dimensional superconductors for quantum tunnelling.
- Single-photon emitters for quantum technology applications in computing.
- Iontronic graphene and layered material-based devices for energy storage systems.
- 'Sandwiched' heterostructures with tailored heat transport and thermoelectric properties for device-level thermal management.



Sensors made using single junctions of hBN-encapsulated bilayer graphene, with significantly improved magnetometer sensitivity. Image credit: University of Manchester

OUR VISION

In the next phase of the project, we will focus on developing new methods for the controlled fabrication of graphene and layered materials, along with characterisation and modelling to broaden the range of functional materials in the family. This will be invaluable for us to design new methods to make ohmic contacts in semiconductors, semimetals and metals.
We will also continue to develop new heterostructures and conduct further studies into their properties. For example, we will use various dry transfer methods, as well as chemical vapour deposition and molecular-beam epitaxy, to grow new layered materials using TMDs as substrates. This will reduce the number of steps needed to manufacture new 'sandwiched' heterostructures.

Furthermore, we will develop new methods for strain engineering, fabricate new superconducting graphene-based materials, and delve into twistronics, exploiting heterostructures with high-precision control of crystalline layer alignment, such as magic-angle graphene, which has new and interesting properties.

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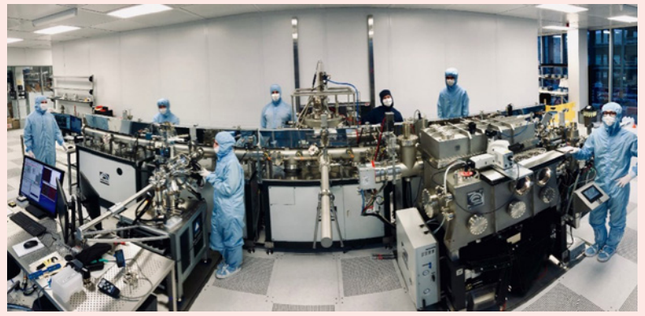
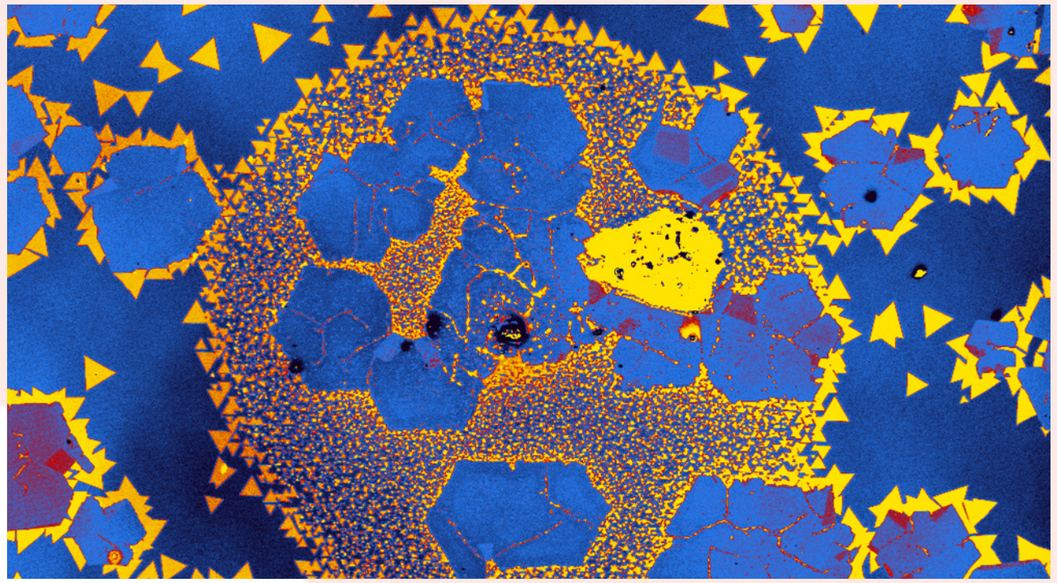
Our findings help other Work Packages to further advance their research and have even enabled us to create new start-up companies: Graphene Lighting, Graphene Security and Eksagon."

Vladimir Fal'ko



Left
The world's first UHV 2DM press, for integrated dry transfer, characterisation and device fabrication in ultra-high vacuum. Image credit: University of Manchester

Bottom
Nucleation of chemical vapour deposited graphene and molybdenum disulfide revealed by confocal laser scanning microscopy. Image credit: NPL Management



Partnering Division

Division Leader
Yuri Svirko, University of Eastern Finland, Finland

Division Deputy
Jan Erik Hanssen, Graphitene Ltd., UK

"The Partnering Division comprises projects, SMEs and large industrial companies, which extend the Graphene Flagship in terms of its technological and research expertise. Since a number of the partnership projects involve members of the Graphene Flagship, the Division facilitates the building of a Europe-wide network of research facilities and experts with outstanding potential for research and innovation in the field of graphene and layered materials," says Yuri Svirko, partnering division leader from the University of Eastern Finland.

TALGA

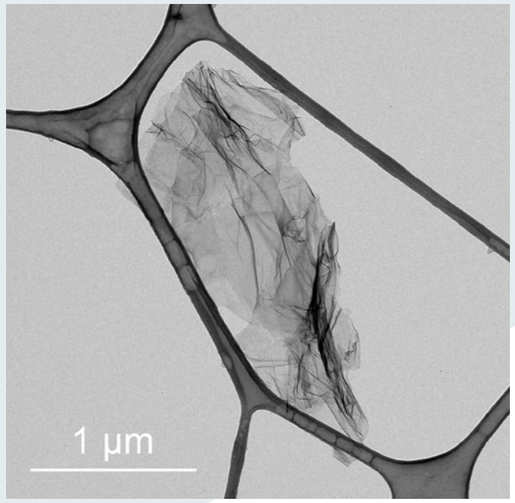
Over the past year, graphene additives and advanced battery anode materials provider Talga Resources Ltd has developed a maritime coating product, Talcoat™, which is now undergoing a large-scale commercial trial on a 33,000-tonne container ship. The Talcoat product, in the form of an on-site dispersible powder, and a 2-part epoxy based commercial coating system were supplied separately and mixed on-site by paint applicators before spray application to the vessel during dry docking, an improvement over normal graphene-based products that typically require factory conditions to be dispersed. The performance of the coating, intended to incorporate graphene's exceptional strength amongst other benefits to the ship's primer coating system, will be evaluated over the next 12 to 18 months.

CoExAN

The development of on-chip integrated carbon-based opto-electronic nanocircuits requires fast and non-invasive structural characterisation of their building blocks. Recent advances in the synthesis of single-wall carbon nanotubes and graphene nanoribbons allow for their use as atomically precise building blocks. However, while catalogued experimental data are available for the structural characterisation of carbon nanotubes, such an atlas is absent for graphene nanoribbons. In 2019, researchers from CoExAN, a Graphene Flagship partnering project, theoretically investigated the optical absorption resonances of armchair carbon nanotubes and zigzag graphene nanoribbons continuously spanning the tube (ribbon) transverse sizes from 0.5(0.4) nm to 8.1(12.8) nm. They showed that linear mapping is guaranteed between the tube and ribbon bulk resonance when the number of atoms in the tube unit cell is 2N+4, where N is the number of atoms in the ribbon unit cell. Thus, an atlas of carbon nanotubes' optical transitions can be mapped to an atlas of zigzag graphene nanoribbons.[1]

GRAPHITENE

Graphitene's wet chemical process offers flexible, 'green' manufacturing of a range of graphene, GO, rGO, doped and microporous graphenes, admixtures and masterbatches. The company highlights the importance of selecting the appropriate natural graphites to achieve optimal properties of its graphene products. Highly conductive graphene is Graphitene's fastest growing product. Lijie He, research scientist at Graphitene's factory and tech centre in Flixborough, England, says "This is one- to three-layer graphene with electric conductivity above 1500 S/m. This graphene is valuable in a variety of applications including conductive inks, lithium batteries, solar cells, conductive coatings, sensor devices and electrode materials."



Over the past year, Graphitene has started a long-term strategic collaboration with Roland Berger, Europe's leading business consultancy, which has been highly productive in identifying and prioritising the key steps to take for cost-effectively addressing the many potential markets Graphitene has been pursuing over the years.

G-IMMUNOMICS

Light exposure of graphitic carbon nitride (g-C_3N_4), a novel 2D material, resulted in the formation of reactive oxygen species, causing the death of cancer cells in vitro and in vivo, as evidenced by classical methods as well as omic approaches. The photo-excitation of g-C_3N_4 could be used effectively in a photodynamic therapy protocol for cancer treatment without any other nanocarrier, additional photosensitiser or chemotherapeutic drug, Graphene Flagship partnering project G-IMMUNOMICS researchers found.[2]

INSTITUTE OF CHEMISTRY, TECHNOLOGY AND METALLURGY

Wrinkles often form on graphene grown using chemical vapour deposition (CVD) on traditional metal substrates such as copper or nickel, as a result of the substrate shrinking as it cools. Recently, molybdenum (Mo) has emerged as an alternative substrate for CVD growth due to a better match of the thermal expansion of the substrate and graphene. Researchers at Graphene Flagship Associate Member the Institute of Chemistry, Technology and Metallurgy, Serbia, have investigated the quality of multilayer graphene grown on Mo and found that the graphene is free of large wrinkles that are common with growth on other metals, although it contains a dense network of small wrinkles. Their work demonstrates that graphene grown on Mo has low friction, high wear resistance and excellent homogeneity of its electrical surface potential and conductivity.[3]

H2O

The H2O partnering project has established chemical vapour deposition growth of large area monolayers of transition metal dichalcogenides (TMD) with high structural and optical quality.[4] In collaboration with the Core Project (Ulm University), H2O showed that the defect density in these 2D materials (e.g., MoS_2, WS_2, $MoSe_2$, WSe_2, etc.) is of the same value as in the monolayers exfoliated from high quality 3D crystals, which results in only a five meV width of the excitonic peak in the grown monolayers. This improvement opens up a broad range of 2D TMD applications in innovative photonic devices.[5]

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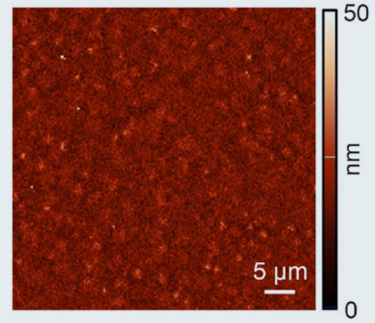
The Partnering Division facilitates the building of a Europe-wide network of research facilities and experts with outstanding potential in research and innovation in the field of graphene and layered materials."

Yuri Svirko

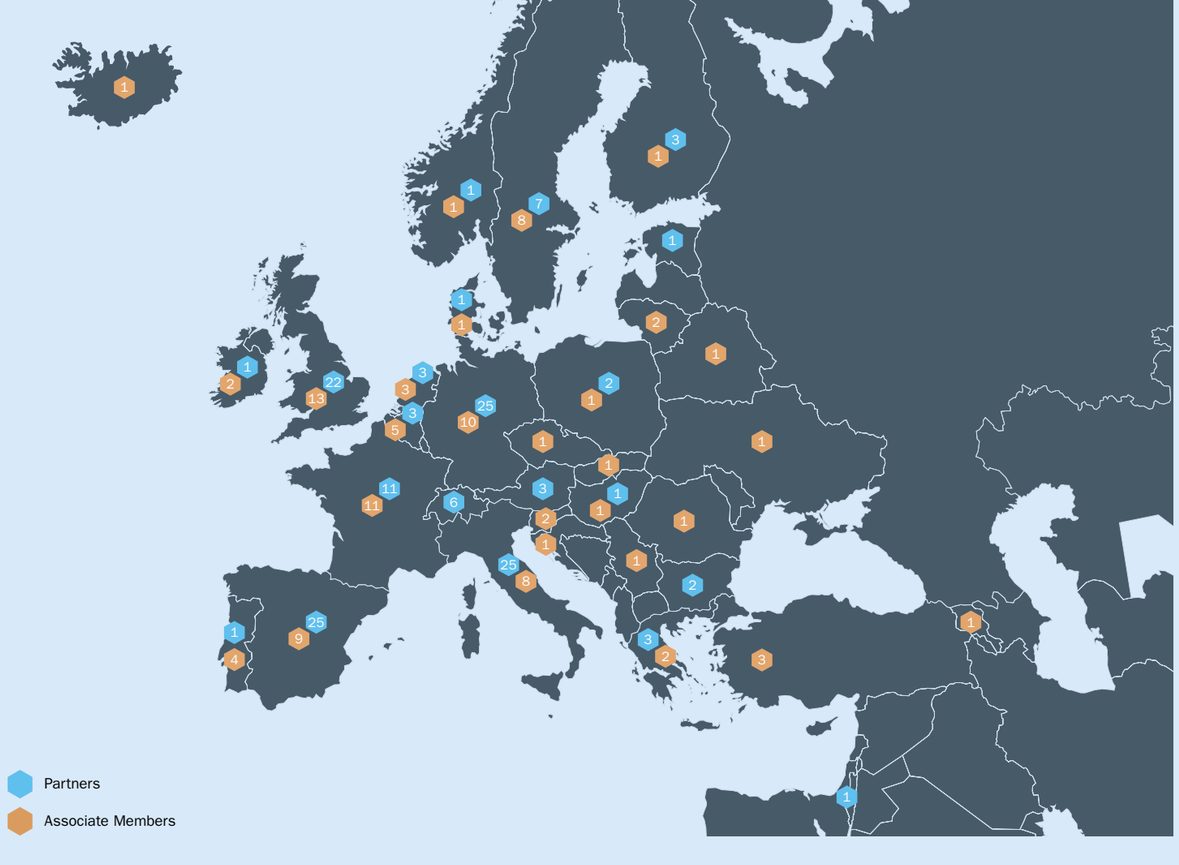


Above
The morphology of CVD graphene on Mo. Image credit: Institute of Chemistry, Technology and Metallurgy

Left page 1
Talcoat™ graphene additive being mixed on-site into commercial 2-part epoxy coating system. Image credit: Talga

Left page 2
A TEM image of Graphitene's HCG taken at Tartu University (Estonia), one of Graphitene's more than 40 academic collaboration partners in Europe and Asia. Image credit: Graphitene

GRAPHENE FLAGSHIP ANNUAL REPORT 2019



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On the Horizon: Core 3 Spearheads

The Graphene Flagship funds a number of Spearhead Projects, initiatives with well-defined, application-oriented objectives that are motivated by market opportunities. These Spearheads focus on a wide range of application areas, but all have the common goal of developing new or improved products with integrated graphene or layered materials.

GRAPHIL

The Graphene Flagship has invested in GRAPHIL, a project for the production of innovative filters for water purification.

With the collaboration of industrial partners Medica SpA, Polymem S.A and Icon Lifesaver, GRAPHIL addresses EU Sustainable Development Goal 6: Clean Water & Sanitation, through the removal of contaminants that are increasingly present in European water sources.

G+BOARD

What does the car of the future look like? G+BOARD believes it will include a unique graphene-based dashboard, designed to improve automotive functionality, reduce production costs and decrease fuel consumption.

With the collaboration of industrial partners, including Avanzare Innovacion Tecnologica in Spain and Nanesa, Bioage SRL, SPAC SpA and automotive heavyweight, Centro Ricerche Fiat, in Italy, G+BOARD aims to create the dashboard of the future.

CIRCUITBREAKERS

Circuit breakers are safety-critical components, but the decomposition of greases used in conventional circuit breakers results in costly maintenance for businesses.

To tackle this problem, CIRCUITBREAKERS, led by industrial partners ABB, Nanesa and GraphMaTech AB, are developing a grease-free circuit breaker, using graphene's self-lubricating properties to save businesses huge maintenance costs.

METROGRAPH

The application market for photonic integrated circuits is rapidly growing, and photonic integration is set to be a dominant technology in high bandwidth communications.

METROGRAPH are developing a wide spectrum high capacity optical transceiver that uses one single technology, graphene photonics, across both the transmitter and receiver, to reduce the costs of photonics integration, and enable uptake in new sectors.

GBIRCAM

The graphene broadband infrared imager for camera systems (GBIRCAM) project is developing a camera that detects visible light (VIS), near-infrared (NIR), short-wavelength infrared (SWIR) and long-wavelength infrared (LWIR) in one single super pixel device, reducing the costs of broad-spectrum imaging.

The broad-spectrum capabilities enable detection beyond the human eye, for quick analysis of organic products, such as food and chemical composition, leading to vastly improved safety for food and pharmaceutical sectors among others.

AEROGRAFT

Keeping contaminants from reaching the passenger cabin of any aircraft is critical. AEROGrAFT is set to produce heatable aero-graphene foams, to reduce the cleaning time of aero-material filters, saving businesses huge sums of maintenance costs and downtime.

This project will explore the use of graphene-foam filters to remove contaminants from cabin air. Their unique qualities allow them to filter out germs which current HEPA filters are unable to eliminate.

GRAPES

Thanks to new thin-film technology, perovskites could bring increased efficiency at a lower cost to solar panel manufacturing. However, perovskites have high instability and low efficiency at large scales.

GRAPES is set to make cost-effective, stable graphene-enabled perovskite panels. The project will play an essential role in improving Europe's uptake of solar energy projects by improving the stability and efficiency of this technology when deployed on a large scale.

AUTOVISION

Autonomous driving is the future, but is it safe? Current self-driving vehicles place passengers and other road users at an unacceptable risk when they operate autonomously in darkness or adverse weather conditions such as rain, fog and snow.

AUTOVISION is developing a new high-resolution image sensor that provides autonomous vehicles with essential data to eliminate the risks associated with autonomous driving in extreme conditions. In collaboration with industrial partners Aixtron in the UK and Veoneer in Sweden, this project will enable safe deployment of autonomous vehicles.

GREENBAT

Charging, range and cost are just some of the concerns regarding electric vehicle batteries. The Graphene Enabled High-Energy Batteries for Automotive Applications (GreenBAT) project will improve battery technology for electric vehicles, helping the EU achieve its ambitious sustainability goals.

Graphene Flagship industrial partners VARTA Micro Innovation, BeDimensional and Varta Microbattery are basing the battery technology on a patented graphene fabrication and silicon-graphene compounding processes.

GICE

Thermoelectric ice protection systems prevent dangerous ice accumulation on aircraft surfaces, and utilising graphene in these systems can increase efficiency without affecting aerodynamic properties.

The graphene-based thermoelectric ice protection system, GICE, is set to advance the technology readiness of graphene in thermoelectric ice protection systems, by developing three technology demonstrators for industrial partners, including Airbus and Sonaca.

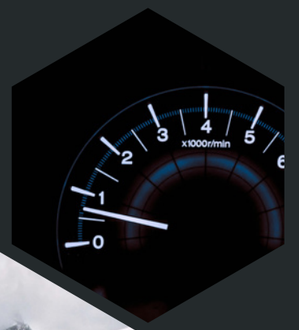
SAFEGRAPH

Bringing any product to market requires regulation and legislation. But for new materials, like graphene, this authorisation pathway does not exist – yet.

SafeGraph aims to bring safe graphene-based products to market, based on regulatory compliance and standard practices. The regulatory consultancy companies Temas and the Swiss Federal Laboratories for Materials Science and Technology, Empa, both based in Switzerland, are joining forces to enable graphene's pathway to commercial application.

All of the Spearhead Projects have strong company involvement and are committed to producing industrial prototypes within two years, in order to spur interest among companies that are currently not involved with the Graphene Flagship."

Jari Kinaret
Graphene Flagship Director



GRAPHENE FLAGSHIP ANNUAL REPORT 2019

The Innovation Era

The Graphene Flagship has gone from strength to strength. Our first six Spearhead Projects, designed to increase the technology readiness level of graphene-based technologies have come to fruition, and many successful prototypes have reached the pilot phase (see page 30). We are now ready for the next developments and further steps towards the commercialisation of new products in the fields of 5G technology, batteries, wearables and more. The next phase of the Graphene Flagship will see the start of eleven new industry-led projects, focusing on key European industrial sectors and covering all areas of innovation we support (see page 60). Moreover, we will launch the first Experimental Pilot Line, an initiative to provide industry in Europe and beyond with the necessary tools to design and manufacture devices based on graphene and layered materials. These devices will soon reach the pilot phase for consumer electronics, sensors, data and telecommunications, and more.

UNLOCKING THOUSANDS OF LAYERED MATERIALS

This new phase also brings a new challenge: defining the future of the Graphene Flagship within Horizon Europe. 2023 will mark the start of the second stage of our ambitious journey, after the initial and very successful 10 years. We will target new applications and embark on a deeper exploration of the virtually infinite set of combinations enabled by the thousands of different layered materials and their ‘sandwiched’ heterostructures. Technologies based on graphene and layered materials are on the verge of a broad industrial revolution in fields as diverse as automotive and aviation, electronics, telecommunications, energy, composites and biomedicine. Thanks to the investment in the Graphene Flagship, Europe is in an excellent position to seize the opportunities offered by these new materials.

AN OPPORTUNITY FOR EUROPEAN INDUSTRY

Another sign of the Graphene Flagship’s success in science, technology and innovation is the strong industrial support across the EU. European industry recognises the three main challenges that lie ahead of us:

- Graphene-based technologies are now reaching the tipping point for mass exploitation, and we need to ensure that Europe reaps the rewards of early investment.
- Thousands of new layered materials have been discovered and need to be explored. Their fundamental science must be understood, and their numerous combinations must be investigated using conceptually new approaches.
- The most promising new layered materials must be taken to the level of maturity we have reached with graphene, and they need to be ready to create further innovation and new technologies.

A PROJECT THAT EVOLVES

During the latest phase of the Graphene Flagship, we saw many new spin-off or start-up companies being born (see page 12), numerous products reaching the market, tens of patents granted, and an influx of new industrial partners and Associate Members. Almost half of our consortium today are companies, compared to the modest 15% we had at the start. The Graphene Flagship is continuously changing to tackle the challenges and take advantage of the opportunities we encounter along the way: two thirds of the current partners were not part of the initial start-up phase. This showcases that the Graphene Flagship is alive, continuously evolving and adapting, but firmly set to deliver on our technology and innovation roadmaps.

GRAPHENE TOWARDS SUSTAINABILITY

The Graphene Flagship is also committed to the 2030 Agenda for Sustainable Development, and will work towards more environmentally friendly research and innovation. The next phase of our project will be closely aligned with the United Nation’s Sustainable Development Goals and intertwined with the European Union’s Green Deal. Among other initiatives, our Validation Service, standardisation projects, focused roadmapping, and the new Spearhead devoted to the health and safety of graphene-enabled products, clearly confirm the world-leading position of the Graphene Flagship on the road to a climate-neutral future (see page 40).

The Graphene Flagship is the place to be, as a partner or Associate Member, for any industry, research centre or university striving to explore the possibilities of graphene and layered materials to enable a new generation of technology and innovation.

Andrea C. Ferrari
Graphene Flagship Science and Technology Officer

The Graphene Flagship is Research, Innovation and Collaboration

Funded by the European Commission, the Graphene Flagship aims to secure a major role for Europe in the ongoing technological revolution, helping to bring graphene innovation out of the lab and into commercial applications by 2023. The Graphene Flagship gathers nearly 150 academic and industrial partners from 21 countries, all exploring different aspects of graphene and layered materials.

Bringing diverse competencies together, the Graphene Flagship facilitates cooperation between its partners, accelerating the timeline for industry acceptance of graphene technologies. The European Commission's FET Flagships enable research projects on an unprecedented scale. With €1 billion budgets, the Graphene Flagship, Human Brain Project and Quantum Flagship serve as technology accelerators, helping Europe to compete with other global markets in research and innovation.

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