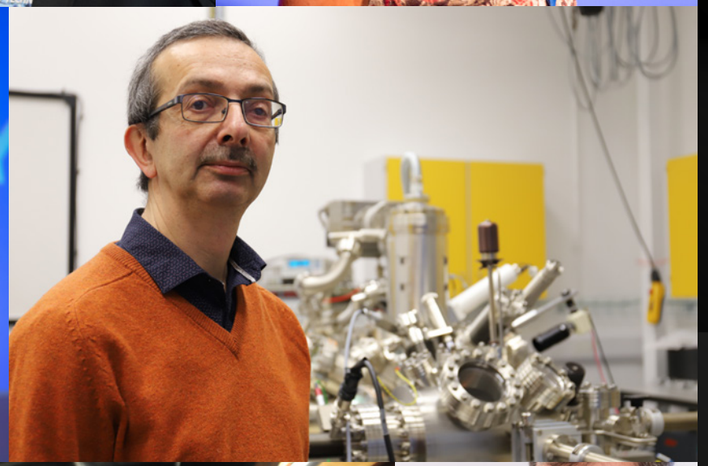
GRAPHENE FLAGSHIP

Funded by the European Union

ANNUAL REPORT 2020







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Above
Meet the Graphene Flagship Dissemination Team: the communications experts who work hard to organise events, spread the word about graphene and get people involved.

In 2020, they coordinated the move to a more digitally inclusive media and events landscape, helping European graphene science and industry to adapt to our ever-changing world.

Below
The European Commission's definition of technology readiness levels from the Horizon 2020 Work Programme (2014): bit.ly/GrapheneTRL

These numbers explain how close a product is to being market-ready, all the way from the drawing board to development and manufacturing.

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

FROM THE DIRECTOR

Portrait of Graphene Flagship Director Jari Kinaret. Credit: Oscar Mattsson

2020 was a special year, and far more interesting than any of us might have hoped for.

We dealt with a global pandemic that greatly affected our lives both inside and outside the Graphene Flagship. Simultaneously, we contended with events like Brexit that would ordinarily be described as cataclysmic, but have now been rendered rather insignificant by comparison.

This was also a year of great achievement. The Graphene Flagship finished its third funding phase, Core 2, sailing into its third Core project and launching the 2D Experimental Pilot Line (2D-EPL). These actions increased the size of our consortium to over 170 partners, evenly divided between commercial actors and academic or research institutions. Roughly one quarter of our partners are new to the consortium, demonstrating our ability to bring in new competence as the Graphene Flagship evolves and moves to higher technology readiness levels (TRLs).

We also saw increased participation from our Graphene Flagship Associated Members, whose number now exceeds 100. Many of them are active in over 30 Partnering Projects, which are often funded by European Union member states and associated countries, demonstrating the commitment of national funding agencies to the goals of the Graphene Flagship.

ON THE ROAD TO COMMERCIALISATION

In 2020, we greatly expanded our high-TRL activities by launching 11 new Spearhead Projects that target specific commercial applications over a wide range of fields, from water purification and sustainable batteries to photonics applications and autonomous driving.

This, together with the growing number of new products and spin-off companies established by Graphene Flagship partners, shows that we have the knowledge and ability to cross the valley of death between academic research and the commercial market. This is the most significant overarching result of the Graphene Flagship thus far.

ADJUSTING TO CHANGE

Our events portfolio was likely the Graphene Flagship activity most significantly affected by the pandemic. The last in-person event we organised was the visit of Margrethe Vestager, the Executive Vice President of the European Commission, to the Graphene Flagship in the spring of 2020.

> We have the knowledge and ability to cross the valley of death between academic research and the commercial market."

Since then, we have hosted all of our events online, and we had to re-invent the wheel several times over as the conditions changed. I am very impressed with how our Event Manager Luciana Löberg and Marketing Manager Sofia Järbur orchestrated and managed the transition in these challenging times.

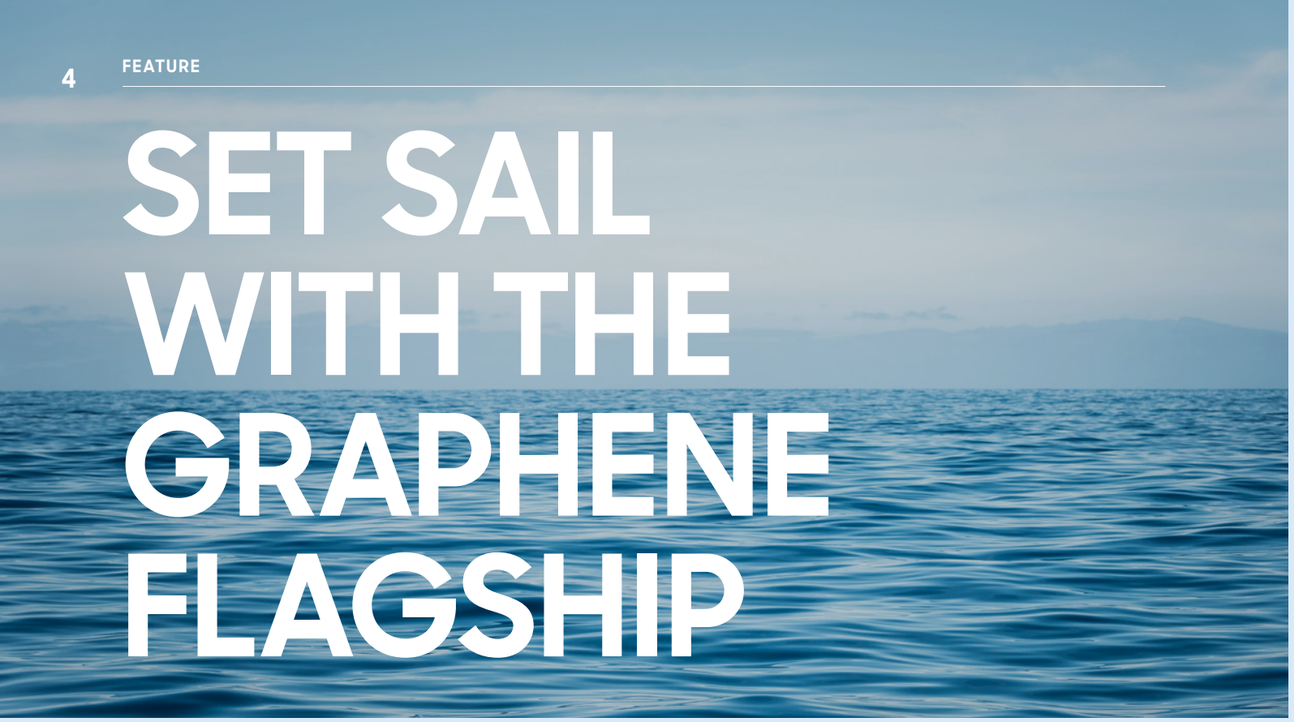
ON THE HORIZON

Looking to the future, we must now start to plan the continuation of our activities within the European Union's next research and innovation framework, Horizon Europe. As I write this statement as 2020 draws to a close, much is still undecided regarding Horizon Europe, but it is evident that many challenges lie ahead of us. Addressing these challenges will be one of our main tasks in 2021.

I hope that in 2021, we will be able to meet in person rather than on Zoom, Webex or Teams. Advancing science and technology is a social activity, and thus far, digital solutions do not offer the same experiences and opportunities as physical meetings. I have yet to enjoy a digital pint or a glass of wine with a colleague. We will need to adjust our behaviour, but I do not want 2020 to become the new normal.

I look forward to a more normal 2021.

Jari Kinaret
Graphene Flagship Director



SET SAIL WITH THE GRAPHENE FLAGSHIP

We are the European Commission's commitment to research, innovation and collaboration

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.

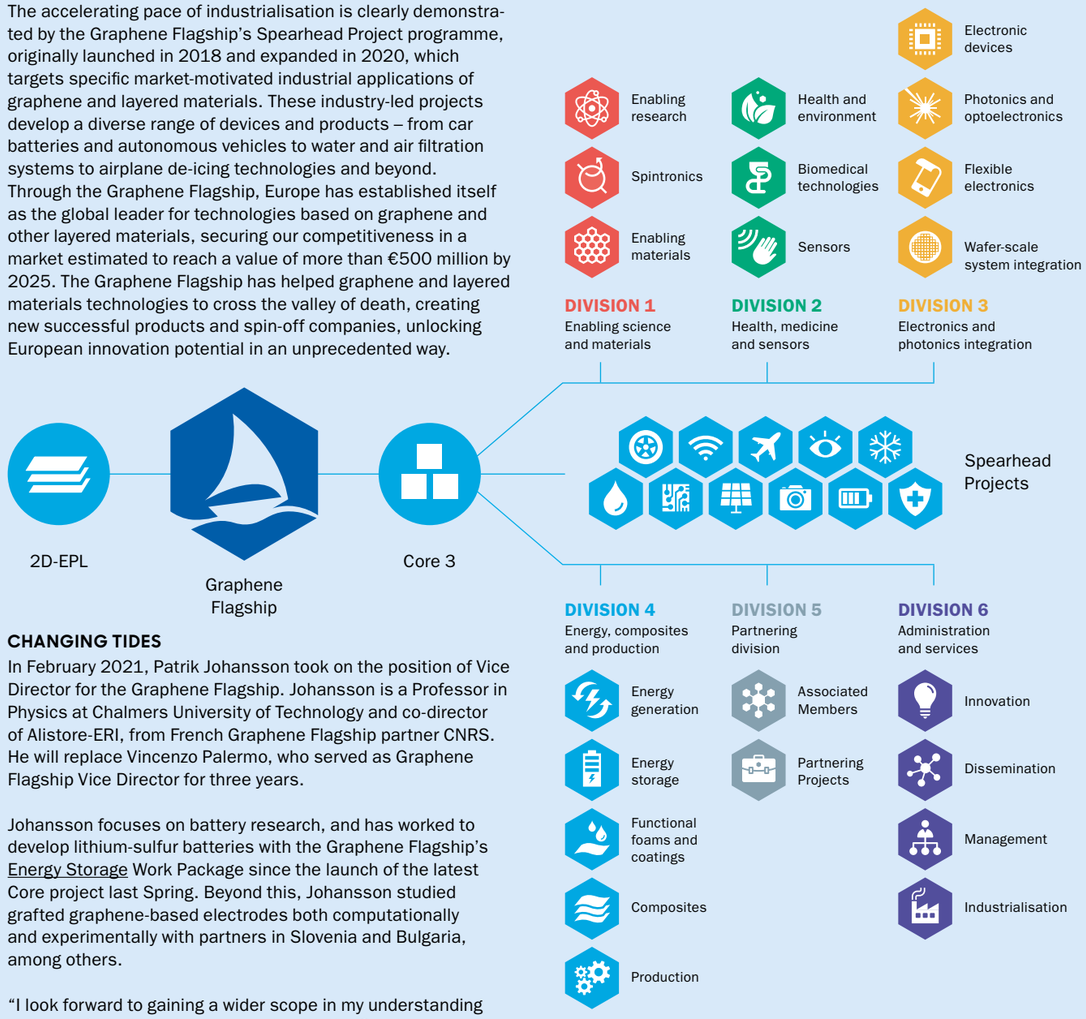
With a €1 billion budget, the Graphene Flagship's Core project gathers over 170 academic and industrial partners from 22 countries, all of whom explore different aspects of graphene and layered materials. By bringing diverse competencies together, the Graphene Flagship facilitates cooperation between its partners, accelerating the timeline for industrial acceptance of graphene technologies.

In April 2020, the Graphene Flagship launched its Core 3 phase under the Horizon 2020 framework. Although we will keep supporting fundamental research, in this new phase, our project will focus on advancing industrial applications. One third of the €150 million budget for this Core phase will be dedicated to high-technology readiness level (TRL) applications. Together, we will sail towards a more sustainable future and achieve our ultimate goal: bringing graphene to the market.

LOOKING BACK

Over the past seven years, the Graphene Flagship has successfully brought graphene out of the lab, creating a fruitful European industrial ecosystem that develops applications of graphene and layered materials. Today, our industrial family includes over 100 companies working together with the Graphene Flagship's academic partners in fields ranging from the automotive and aviation industries to electronics, energy, composites and biomedicine. The proportion of companies has grown from just 15 at the launch of the Graphene Flagship to roughly 50% of the consortium today, demonstrating the success of the European Commission (EC)'s Flagship concept.

The accelerating pace of industrialisation is clearly demonstrated by the Graphene Flagship's Spearhead Project programme, originally launched in 2018 and expanded in 2020, which targets specific market-motivated industrial applications of graphene and layered materials. These industry-led projects develop a diverse range of devices and products – from car batteries and autonomous vehicles to water and air filtration systems to airplane de-icing technologies and beyond. Through the Graphene Flagship, Europe has established itself as the global leader for technologies based on graphene and other layered materials, securing our competitiveness in a market estimated to reach a value of more than €500 million by 2025. The Graphene Flagship has helped graphene and layered materials technologies to cross the valley of death, creating new successful products and spin-off companies, unlocking European innovation potential in an unprecedented way.

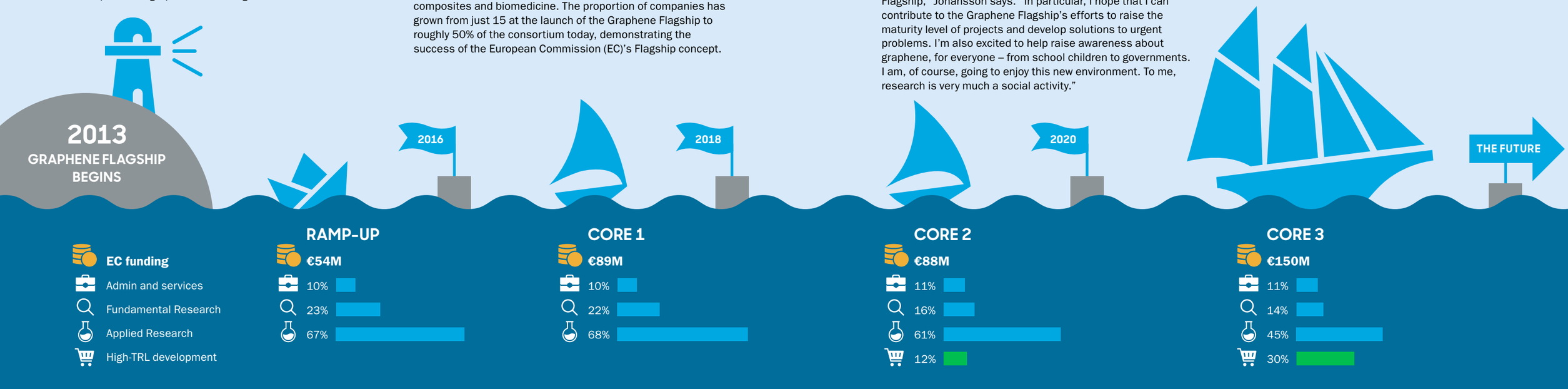


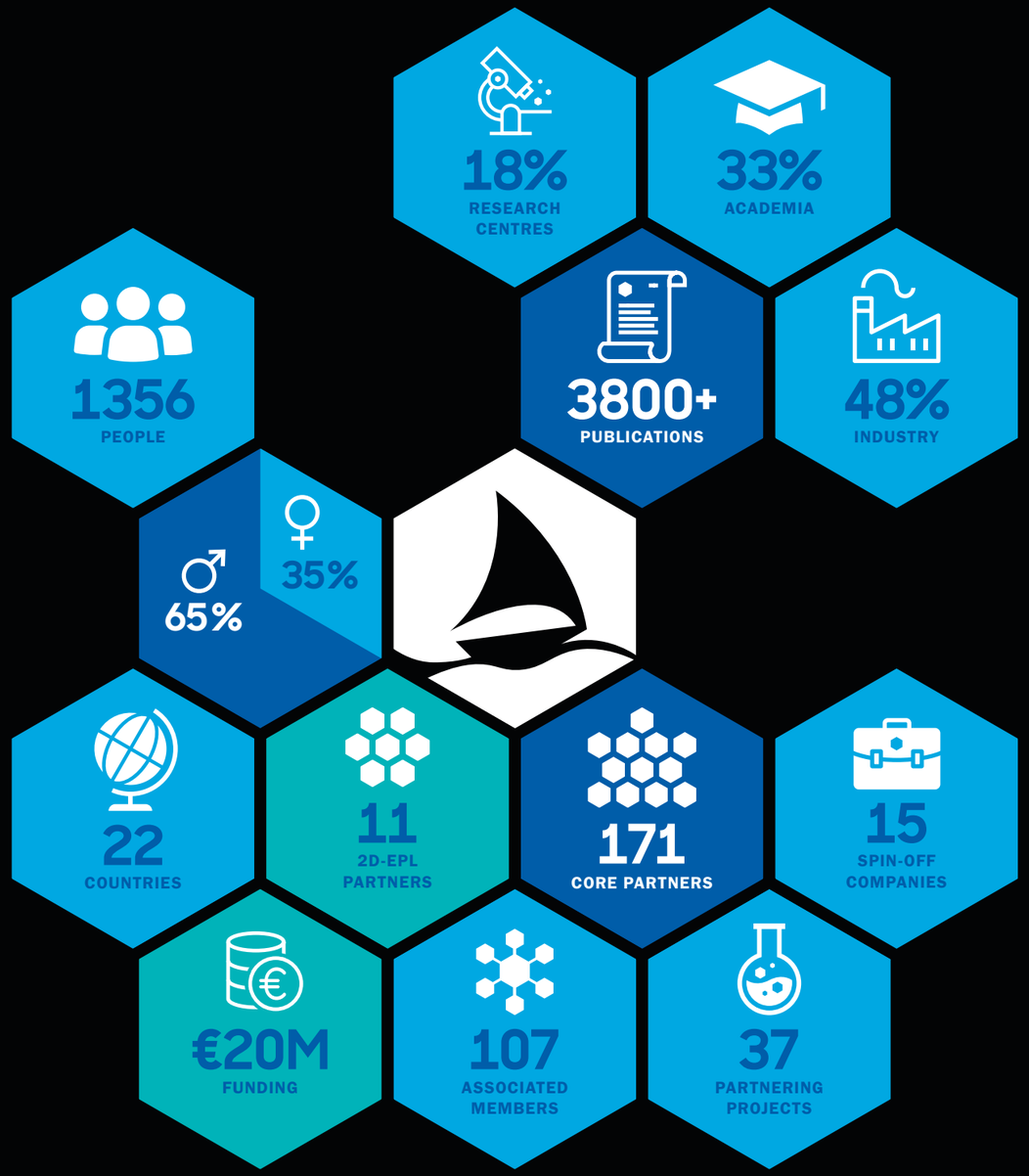
CHANGING TIDES

In February 2021, Patrik Johansson took on the position of Vice Director for the Graphene Flagship. Johansson is a Professor in Physics at Chalmers University of Technology and co-director of Alistore-ERI, from French Graphene Flagship partner CNRS. He will replace Vincenzo Palermo, who served as Graphene Flagship Vice Director for three years.

Johansson focuses on battery research, and has worked to develop lithium-sulfur batteries with the Graphene Flagship's Energy Storage Work Package since the launch of the latest Core project last Spring. Beyond this, Johansson studied grafted graphene-based electrodes both computationally and experimentally with partners in Slovenia and Bulgaria, among others.

"I look forward to gaining a wider scope in my understanding and use of graphene in my new role with the Graphene Flagship," Johansson says. "In particular, I hope that I can contribute to the Graphene Flagship's efforts to raise the maturity level of projects and develop solutions to urgent problems. I'm also excited to help raise awareness about graphene, for everyone – from school children to governments. I am, of course, going to enjoy this new environment. To me, research is very much a social activity."





*Data from Core 3 Month 6 reporting (October 2020).

ON THE HORIZON
In 2021, the European Commission will launch its next research and innovation funding programme, which will change the way in which the Flagships launched in Horizon 2020 will operate. Horizon Europe will incorporate research and innovation missions to increase the effectiveness of funding by pursuing clearly defined targets.

IN THE SPOTLIGHT

The Graphene Flagship is a wonderful and unique initiative that brings together a very large research community and enables it to really work together towards common goals. This experience is very precious, as it shows that, despite all the challenges, this kind of action can work and produce results."

Ana Helman
European Science Foundation
Science Connect, France

Presenting my work as an Associated Member at Graphene Flagship Work Package meetings and discussing it with international peers really helped to clarify my vision and place it in the context of current global trends. I also established active collaborations in areas that we cannot cover on our own, which significantly widened the impact of my work."

Marko Spasenović
Institute of Chemistry
Technology and Metallurgy, Serbia

Scientific growth and innovation are positively related to the sharing of ideas and laboratory experiences. Bringing together people from different backgrounds expands the range of knowledge and enhances the research skills of everyone involved. In my opinion, promoting diversity can be the key element to generating a wide array of ideas, improving research, and developing new products and applications of graphene."

Audrey Franceschi Biagioni
SISSA, Italy

By developing a European pilot line for the processing of graphene and layered materials, we aim to bring these innovative materials from the academic laboratories to the semiconductor production lines. We want to offer early access to experimental pilot line production to the innovative graphene community in Europe."

Cedric Huyghebaert
imec, Belgium

MEET THE SPEARHEADS

Discover the Graphene Flagship's industry-focused Spearhead initiative

The Spearhead Projects are initiatives designed to increase the technology readiness level (TRL) of graphene-based technologies. Each Spearhead Project is led by an industry-leading company and has specific commercial goals. They each aim to produce a high-TRL prototype or market-ready product by the end of the current phase of the Graphene Flagship in 2023. The Graphene Flagship's commitment to the Spearhead Projects is unshakeable: a total of one third of our funding is invested into these ventures, a bold move to maximise the impact of the Graphene Flagship in the innovation ecosystem and the European economy.

The Graphene Flagship Spearhead Projects all align with the United Nations' 17 Sustainable Development Goals. The projects' objectives include using graphene-enabled products to ensure good health and wellbeing, guarantee clean water and sanitation, generate affordable and clean energy, and create sustainable cities and communities – as well as making improvements to industry, innovation and infrastructure in Europe.

For instance, GRAPES is a project to develop cost-effective, stable graphene-based perovskite solar panels, and AUTOVISION is developing a new high-resolution image sensor for autonomous vehicles. GICE is working on graphene-based ice protection technologies for aircraft, and GRAPHIL seeks to make next-generation filters to remove contaminants from water.

In this section, take a deep dive and learn about the 11 Spearhead Projects coordinated by the current phase of the Graphene Flagship.

GRAPHIL

Project Leader
Letizia Bocchi, Medica, Italy

Industrial Leader
Medica, Italy

Project Deputy
Manuela Melucci, National Research Council, Italy

Developing compact water filters based on graphene

The GRAPHIL Spearhead Project works to produce innovative water filters that can easily be connected directly to a household sink, or used as a portable water purification device, to ensure easy access to safe drinking water for a sustainable cost. To this end, GRAPHIL aims to manufacture a compact filtration system using polymeric hollow fibre membranes blended with graphene.

GRAPHIL's filters will combine membrane filtration and absorption mechanisms to remove both microbiological and inorganic contaminants. Ultrafiltration and microfiltration allow for the removal of bacteria and pathogens, while graphene-enabled adsorption targets inorganic contaminants.

HIGHLIGHTS FROM 2020

Over 2020, GRAPHIL explored two different parallel approaches to blend graphene with hollow fibres: one by making composites of graphene oxide and polymers during the hollow fibre spinning process, and another by producing graphene oxide coatings after fibre spinning.

The results are encouraging for both approaches. Graphene Flagship partner the National Research Council (CNR), Italy, developed a standard procedure to rapidly characterise and compare the performance of fibres. Their lab experiments were performed with a mixture of three contaminants, including antibiotics and dyes.

GRAPHIL is also evaluating the efficiency for the removal of perfluorurated compounds, a class of contaminants with growing environmental concern. They demonstrated that using more graphene oxide increases the amount of contaminant removed.

TOWARDS MARKET-READY RESULTS
We expect to have a product ready for the market by 2023 to 2024.

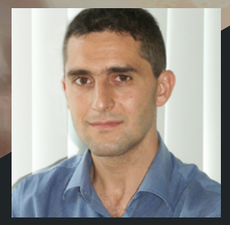
SUSTAINABLE DEVELOPMENT

One of the biggest challenges of the 21st century is to provide access to safe, clean water for everyone, and to reduce the plastic waste resulting from bottled water consumption. European water quality is generally high, but many factors contribute to an increase in the number of contaminants released into the environment every day. No current technology is able to remove all of these contaminants.

The European Union are proposing a revision of the Drinking Water Directive, which regulates water for human consumption, to curb pollutants and encourage people to drink tap water. GRAPHIL was conceived to make sure everyone has clean and safe tap water, working directly towards this goal.

PARTNERS
Medica, Italy
National Research Council, Italy
Chalmers University of Technology, Sweden
Polymem, France
Icon Lifesaver, UK
University of Manchester, UK

G+BOARD



Project Leader
Brunetto Martorana, Fiat Research Centre, Italy

Industrial Leader
Fiat-Chrysler Automobiles, Italy

Project Deputy
Vincenzo Palermo, National Research Council, Italy

Using graphene and layered materials to develop integrated, copper-free car dashboards

G+BOARD will produce an integrated copper-free automotive dashboard for cars, consisting of an upper instrument panel and a steering wheel. The dashboard will feature conductive patterns, sensors and devices based on multi-functional graphene or reduced graphene oxide. The G+BOARD project will replace the copper wiring and buttons currently used in car dashboards, reducing the number of production steps and lowering vehicle weight, whilst also improving aesthetics and recyclability.

The multi-functional properties of graphene and layered materials will be used to selectively modify the electrical conductivity of the dashboard polymer material. This can allow for internal signal transport and wireless conductive circuits, by replacing traditional copper wiring with integrated conductive paths, as well as sensors and switches to enable better communication between the driver and the environment.

The G+BOARD Spearhead Project aims to upgrade Fiat-Chrysler's dashboard, to improve automotive functionality, reduce production costs for manufacturers and decrease fuel consumption for end users. Credit: Fiat Chrysler Automobiles

HIGHLIGHTS FROM 2020

In 2020, G+BOARD defined the technical requirements for the final set of components, identifying which materials are needed in accordance with their intended applications and targets. G+BOARD also formulated new polymer compounds based on graphene and layered materials, and carried out testing and characterisation.

SUSTAINABLE DEVELOPMENT

G+BOARD intends to produce complex electrical systems, processed by laser writing inside polymer-based materials, thus reducing the weight of vehicle components and making them easier to recycle. The novel laser writing technology will enable multifunctional components that are fully recyclable, constructed entirely from thermoplastic resin with a small amount of carbonaceous filler.

TOWARDS MARKET-READY RESULTS
By the end of the project, the new technologies will be integrated into a concept car for Fiat-Chrysler. The car's introduction to the market will be linked to the development timescale for a new concept vehicle.

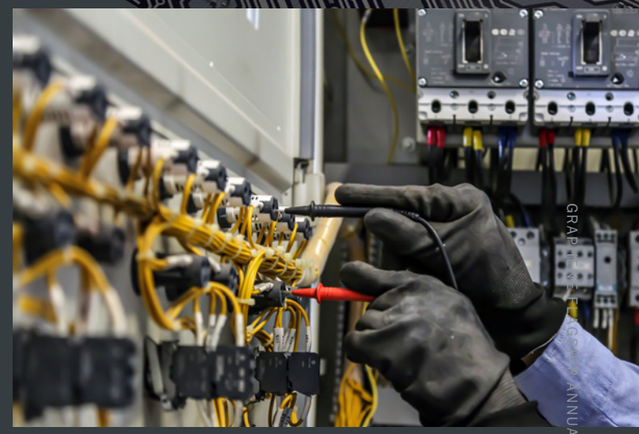
PARTNERS
Fiat Research Centre, Italy
National Research Council, Italy
The University of Cambridge, UK
FORTH, Greece
Avanzare, Spain
Nanesa, Italy
Bioage, Italy
SPAC, Italy

Circuitbreakers

Project Leader
Anna Andersson, ABB, Sweden

Industrial Leader
ABB, Sweden

Project Deputy
Francesco Bertocchi, Nanesa, Italy



Designing innovative circuit breakers to protect the electrical grid

The objective of the Circuitbreakers Spearhead Project is to enable first-of-their-kind grease-free, maintenance-free, low-voltage circuit breakers for fault protection in key parts of the electrical grid. Replacing lubricating grease with self-lubricating metal–graphene composites will substantially reduce the need for maintenance and service, as well as extending the lifetime of these critical devices.

The technology was developed by the Graphene Flagship for electrical contacts, and has now been adapted and scaled for circuit breaker applications. The metal–graphene solution will be provided as a coating made by cost-effective electroplating, or as composite parts produced by sintering.

HIGHLIGHTS FROM 2020

The Circuitbreakers team worked with many of our European partners to narrow down the most suitable materials for electroplating and sintering, and to optimise the processes to make them scalable. For instance:

- ABB Corporate Research, Sweden, defined specifications for material requirements
- Chalmers University of Technology (CUT), Sweden, benchmarked different graphene materials to create a baseline of raw materials
- CUT, Sweden, and FORTH, Greece, evaluated different functionalisation routes
- Nanesa SRL, Italy, evaluated different electroplating process conditions and morphologies of graphene and layered materials for metal-graphene coatings
- The University of Rome Tor Vergata, Italy, evaluated and confirmed the importance of different treatment processes
- Graphmatech AB, Sweden, prepared sintered composite metal–graphene components using selected metal powders and their proprietary ArosGraphene® material.

The Circuitbreakers team also took initiatives towards industrialising their two different processing routes.

SUSTAINABLE DEVELOPMENT

Low-voltage circuit breakers minimise losses from friction. The Circuitbreakers project enables smart and sustainable grid solutions, for the distribution and industrial sectors, by utilising water-based electroplating processing, carbon-based components and recyclable materials.

TOWARDS MARKET-READY RESULTS
Circuitbreakers is on-target to provide market-ready results by the end of the current phase of the Graphene Flagship project in 2023.

PARTNERS
ABB Corporate Research, Sweden
Graphmatech, Sweden
Nanesa, Italy
Chalmers University of Technology, Sweden
The University of Manchester, UK
The University of Rome Tor Vergata, Italy
FORTH, Greece

METROGRAPH

Project Leader
Paola Galli, Nokia, Italy

Industrial Leader
Nokia, Italy

Project Deputy
Vito Sorianello, CNIT, Italy

Developing graphene-based photonic chips for better optical communications

METROGRAPH is developing a wavelength agnostic, coherent optical transmitter and receiver based on graphene photonic chips for low-cost, high bandwidth communications. The device will operate at 200 GBaud/s in the conventional band and long-wavelength band, covering the 1530–1625 nm wavelength range.

The transmitter and receiver will consist of two graphene-integrated IQ modulators and eight detectors. The graphene-based photonic circuits will be packaged and tested both in the lab and in a network line card with a technology readiness level of 8, together with a state-of-the-art digital signal processor. Their functionality will be demonstrated in equipment for metro and metro-regional distances of 200 to 1000 kilometres.

The internet network, which is based on optical communications and wide-bandwidth communication, enables people and both public and private services to have open access to information for education, work, healthcare and more. METROGRAPH is developing advanced communications technologies which could contribute to the improvement of these networks.

HIGHLIGHTS FROM 2020

METROGRAPH developed an IQ modulator and a coherent receiver to validate their design in the laboratory. They also prepared the package design for the assembly of a Nokia line card.

SUSTAINABLE DEVELOPMENT

Optical communications enable the internet and communications technologies of the modern day. Furthermore, they contribute to most of the sustainable development goals agreed by the United Nations in the 2030 Agenda for Sustainable Development.

TOWARDS MARKET-READY RESULTS
A prototype will be ready by 2023. METROGRAPH will also conduct prequalification processes on a number of line card replicas, followed by customer testing.

PARTNERS
Nokia Solutions and Networks, Italy
Nokia Solutions and Networks, Germany
Finisar II-VI, Germany
CNIT, Italy
imec, Belgium
The University of Cambridge, UK

GRAPES

Project Leader
Marina Foti, Enel Green Power, Italy

Industrial Leader
Enel Green Power, Italy

Project Deputy
Antonio Agresti, University of Rome Tor Vergata, Italy

Making cost-effective and stable photovoltaic panels based on graphene and layered materials

Thanks to new thin-film technology, perovskites could bring increased efficiency to solar panel manufacturing for a lower cost. Silicon solar cells are gradually reaching their theoretical upper power conversion efficiency limit, and at the same time, perovskite solar cells have emerged as low-cost solutions for photovoltaics, below $0.3 per Watt, with high efficiencies of over 25%.

The GRAPES Spearhead Project aims to combine these two technologies to design, fabricate and characterise perovskite/silicon tandem solar cells based on graphene and layered materials. By exploiting layered materials like graphene, the GRAPES team aims to boost the performance and stability of perovskite cells to record levels, and to fabricate cost-effective, stable photvoltaic panels based on graphene and layered material–perovskite/silicon tandem technology.

These innovative devices will be realised in an industrially relevant environment: a pilot line with a market readiness level above 6. The panels will be tested using accelerated lifetime tests under real outdoor conditions, with a focus on reducing the levelised cost of energy to below €20 per MWh.

HIGHLIGHTS FROM 2020

GRAPES developed a fully dry-transfer method for single layer graphene on perovskite subcells with high conductivity and transparency.

The industrial partners of GRAPES identified materials for panel lamination compatible with both perovskite and crystalline silicon solar cells. They also defined the inverter requirements by analysing necessary adaptations to the perovskite tandem cells, and upgrading the existing solar farm infrastructure.

SUSTAINABLE DEVELOPMENT

GRAPES focuses on improving the stability and efficiency of solar cells when deployed on a large scale. In turn, this will play an essential role in boosting Europe's uptake of solar energy projects.

TOWARDS MARKET-READY RESULTS
GRAPES will install solar panels 20 m^2 in size with power conversion efficiencies above 23%, outperforming the most powerful silicon module on the market.

The outdoor test, equipped with adapted inverters and a performance monitoring system, will showcase the potential of this technology to industry, helping to commercialise graphene-enabled perovskite cells.

PARTNERS
Enel Green Power, Italy
SIEMENS, Germany
Greatcell Solar Italia, Italy
University of Rome Tor Vergata, Italy
Hellenic Mediterranean University, Greece
The University of Cambridge, UK
Swiss Federal Institute of Technology, Lausanne, Switzerland

AEROGrAFT

Project Leader
Christopher Petermann, Lufthansa Technik, Germany

Industrial Leader
Lufthansa Technik, Germany

Project Deputy
Rainier Adelung, Christian-Albrechts University of Kiel, Germany

Making graphene-based self-cleaning filters for the aerospace industry

The AEROGrAFT Spearhead Project is set to produce heatable foams made from aerographene, a very low-density graphene-based material, to reduce the time needed to clean filters for the aerospace industry. They result in even heating throughout the air filter, which means that all surfaces of the air filter can be consistently and equally cleaned. At the same time, the same graphene foam can be used repeatedly without becoming unstable.

Once certified, these self-cleaning air filters will be ready for commercial applications, saving money in terms of reduced maintenance costs for the aerospace sector.

HIGHLIGHTS FROM 2020

During the concept evaluation phase, the AEROGrAFT team investigated the implementation of two possible product development options with different designs and performance requirements for the later certification process. One product concept was designed and is currently being detailed. AEROGrAFT researchers also tested aerographene in filters against the requirements for each implementation scenario. In particular, they focused on material output and probe dimensions.

SUSTAINABLE DEVELOPMENT

State of the art HEPA filters, currently used in aircraft, need to be changed and disposed of once or twice a year, depending on the flight cycles. The new graphene-based filter with a self-cleaning function will extend their lifetime.

The inside of a Lufthansa aeroplane. Credit: Lufthansa Technik

The upscaled aerographene foam. Credit: Christian Albrecht Universität

Top: The zinc oxide network used by AEROGrAFT. Credit: Christian Albrecht Universität

TOWARDS MARKET-READY RESULTS
The end goal of the AEROGrAFT Spearhead Project is to produce foams in volumes of over 200 cm^3 that remain stable over hundreds of cycles.

PARTNERS
Lufthansa Technik, Germany
PhiStone, Germany
Naturality, France
Sixonia Tech, Germany
Christian-Albrechts University of Kiel, Germany
Technische Universität Dresden, Germany

GBIRCAM

Project Leader
Tapani Ryhänen, Emberion, Finland

Industrial Leader
Emberion, Finland

Project Deputy
Aapo Vartula, VTT, Finland

Developing a graphene-based superpixel camera to detect visible, short-wave and mid-wave IR light

The goal of the GBIRCAM Spearhead Project is to develop a broadband camera based on a graphene-enabled image sensor that can detect visible, short-wave infra-red and mid-wave infra-red light using a single focal plane array. The image sensor will have a resolution of 80 x 60 superpixels, divided into three pixels for each different spectral range.

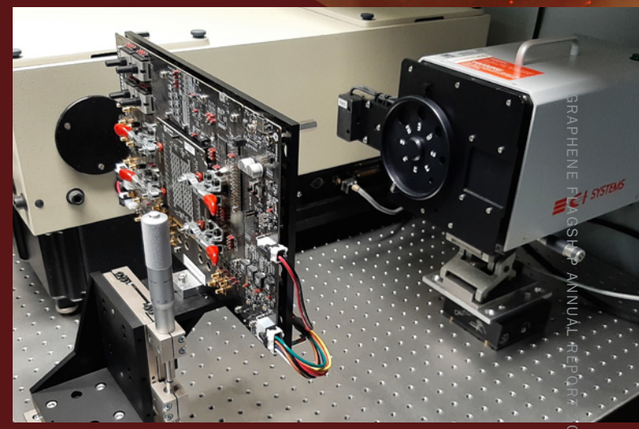
This novel camera will be based on Emberion's modular camera electronics and mechanics, allowing for the image sensor technology to be tested in various industrial environments, like food processing and plastic waste sorting.

Using graphene transducers makes it possible to integrate different light absorbers in the same device, as well as making the overall integrated circuit simpler and easier to implement.

HIGHLIGHTS FROM 2020

GBIRCAM developed absorber material solutions covering the full spectral band. The team studied three different material systems in combination with graphene transducers: colloidal quantum dots, pyroelectric thin films and narrow bandgap oxide nanoparticles. They also investigated the integration of these materials into complementary metal-oxide-semiconductor (CMOS) test wafers with patterned graphene.

The GBIRCAM team successfully tested the functionality of the first version of the 80 x 60 superpixel on a CMOS readout integrated circuit (ROIC). The ROIC is now ready for the integration of graphene and photosensitive materials. As a result, the GBIRCAM Spearhead Project will also benefit from the Experimental Pilot Line's capabilities for graphene transfer and patterning on the wafer scale.



Infra-red setup with a baseboard being tested for the Graphene Flagship. Credit: VTT

SUSTAINABLE DEVELOPMENT

GBIRCAM will have a major impact on the waste sorting, plastic and food industries, as well as on environmental monitoring. This is because a broad wavelength range enables new hyperspectral and spectroscopic solutions. For example, the new technology will allow for the detection and sorting of all types of plastic, including black plastics, which are major polluters on a global scale.

TOWARDS MARKET-READY RESULTS
The image sensors based on Emberion's ROIC circuitry will be integrated by the end of Core 3, the current phase of the Graphene Flagship, which will come to a close in 2023.

PARTNERS
Emberion, Finland and UK
VTT, Finland
Graphenea, Spain
The University of Cambridge, UK

AUTOVISION

Project Leader
Stijn Goossens, Qurv Technologies, Spain

Industrial Leader
Qurv Technologies, Spain

Project Deputy
Steven Brems, imec, Belgium

A new graphene-based high-resolution image sensor for autonomous vehicles

The AUTOVISION Spearhead Project aims to develop a graphene-based image sensor for short-wave infra-red radiation (SWIR), and integrate it in a suitable camera system for self-driving cars.

High-intensity sunlight, fog, poor street lighting and other common low visibility conditions are some of the main challenges for the reliable deployment of advanced driver assistance systems (ADAS) and automated driving systems (ADS). The current state-of-the-art cameras used in these vehicles rely on visible light, which means they perform poorly in low visibility.

Cameras based on SWIR have a clear performance advantage over current technologies: they experience less ambient light interference and less scattering, and hence are able to generate clearer images. SWIR cameras are traditionally based on image sensors made from materials with low manufacturability and high costs, such as indium gallium arsenide, which hinders their uptake into the automotive market.

Qurv's wide-spectrum complementary metal-oxide-semiconductor (CMOS) sensing solution can bring the advantages of SWIR cameras to ADAS and ADS for a cost compatible with high-volume applications.

HIGHLIGHTS FROM 2020

imec, AIXTRON and ICFO, partners of AUTOVISION and the Graphene Flagship, defined a method for wafer-scale graphene growth and transfer that is directly compatible with imec's layered materials contact module. The method for graphene growth and transfer flow makes use of standard semiconductor equipment tools. Furthermore, AIXTRON grew high-quality graphene on 300 mm wafers using their MOCVD reactor technology, ready for integration by imec.

In addition, Veoneer and Qurv worked together to define a test suite for camera benchmarking. The AUTOVISION camera will compete with state-of-the-art visible and SWIR cameras and LiDAR systems.

SUSTAINABLE DEVELOPMENT

AUTOVISION is a step towards autonomous vehicles. By safely allowing humans to take their hands off the steering wheel, autonomous technology could potentially prevent 90% of car collisions every year, saving lives and hundreds of billions of dollars, as well as reducing carbon emissions.

Sustainable mobility also means safe mobility. With approximately 25,000 annual fatalities on European roads, the EU is far away from Vision Zero's goal of eliminating deaths and serious injuries on European roads. Automation will not only improve traffic safety, but also help to reduce energy consumption and avoid traffic jams. Producing key technological solutions will put Europe on course to achieve the 'triple zero goal' of zero emissions, zero congestion and zero accidents.

TOWARDS MARKET-READY RESULTS

AUTOVISION will conduct extended testing and embark on further activities to industrialise their product and highlight the value of SWIR vision for the automotive industry. By working with Veoneer, one of the leading automotive suppliers of ADAS and ADS, AUTOVISION will accelerate the market introduction of their devices and align them with automotive quality and safety standards.

PARTNERS

Qurv Technologies, Spain
imec, Belgium
Aixtron, UK and Germany
Veoneer, Sweden
ICFO, Spain

GrEEnBat

Project Leader
Stefan Koller, Varta Microinnovation, Austria

Industrial Leader
Varta Microinnovation, Austria

Project Deputy
Andrea Gamucci, BeDimensional, Italy

Designing and fabricating silicon/graphene electrodes for automotive batteries

The GrEEnBat Spearhead Project aims to scale up the fabrication of silicon/graphene composite electrodes for anodes in lithium–ion batteries, and to develop a fully functional battery module for automotive applications.

The key innovation of this device was developed and patented during the previous phases of the Graphene Flagship project. All of the targeted specifications for materials, cells and modules will be able to compete with the predicted state-of-the-art modules in 2025.

HIGHLIGHTS FROM 2020

GrEEnBat's research and development efforts in 2020 focused on upscaling the production of high-quality anode materials to the tonne-per-year scale. Their team surpassed the areal capacity and cyclability of the same electrodes produced in the previous phase of the Graphene Flagship by 40% and 10%, respectively.

The team also worked to optimise their electrode recipe, electrolyte formulation and cell design. Full cell testing helps to narrow down the target specifications for the future construction of prototype cells and demonstration of the module.

SUSTAINABLE DEVELOPMENT

If electricity is generated from sustainable and renewable sources, lithium-ion batteries for automotive applications and electric mobility can greatly contribute to reducing global emissions of greenhouse gases.

TOWARDS MARKET-READY RESULTS

By the end of the current phase of the Graphene Flagship in 2023, GrEEnBat plans to enter the four-year automotive development cycle with their battery module.

PARTNERS

BeDimensional, Italy
BMW, Germany
CEA, France
VARTA Microbattery, Germany
VARTA Microinnovation, Austria

GICE

Project Leader
Fabien Dezitter, Airbus, France

Industrial Leader
Airbus, France

Project Deputy
Guillaume Fievez, Sonaca, Belgium

Using graphene to protect aircraft from ice accumulation

Ice accumulation on the wings, propellers and other aircraft surfaces can be extremely dangerous, and graphene-based de-icing systems can offer an alternative low-weight, highly efficient and flexible solution. Easy-to-integrate and versatile electrothermal technology for ice protection systems will play a major role in next-generation aeronautical products, like wings, rudders, rotor blades, air inlets, antennae and windshields.

GICE's goal is to advance graphene-based ice protection technologies to high technology readiness levels (TRLs). GICE aims to produce three demonstrations for specific applications, tailored to the needs of GICE's industrial partners, primarily Airbus and Sonaca: a slat for large aircraft, a rotor blade for helicopters and an air inlet.

HIGHLIGHTS FROM 2020

GICE assessed the maturity of the technologies developed by Graphene Flagship partners. The team characterised the physical and chemical properties of graphene and layered materials, and delivered the first graphene-based heater elements. They also defined the concept for a graphene-based ice detector and evaluated it in a laboratory environment.

SUSTAINABLE DEVELOPMENT

Lowering power consumption and greenhouse gas emissions are essential aspects for GICE. The graphene-based technology, together with an optimised architecture for ice protection systems, are expected to contribute to reducing weight and power consumption by 30 to 40% in helicopters. For large aircraft, integrating ice protection onto the wings will enable better natural laminar flow or hybrid laminar flow, also decreasing power and fuel consumption.

TOWARDS MARKET-READY RESULTS
GICE aims to achieve a TRL above 4 by the end of the current Core phase of the Graphene Flagship. They expect to produce market-ready technology two to five years later, following the necessary validation in relevant environments.

PARTNERS
Airbus, France
The University of Cambridge, UK
Versarien, UK
Free University of Brussels, Belgium
National Research Council, Italy
FORTH, Greece
Nanesa, Italy
FIDAMC, Spain
Sonaca, Belgium

SafeGraph

Project Leader
Peter Wick, EMPA, Switzerland

Industrial Leader
EMPA, Switzerland

Project Deputy
Ester Vázquez, University of Castilla-La Mancha, Spain

Assessing graphene's safety for applications in aerospace, water treatment, wearables and sensors

The SafeGraph Spearhead Project investigates the impact of graphene and layered material-enabled products on human health and environmental safety, focusing on their manufacture, utilisation and life cycle. SafeGraph aims to identify the risk assessment steps and market regulations for four different sectors: aircraft, water treatment, wearable devices and sensors.

SafeGraph supports the following four Graphene Flagship Spearhead Projects:

- ChemSens, developing sensors to be placed on the skin for medical applications
- Weargraph, developing wearable energy generators
- GRAPHIL, designing and fabricating point-of-use filters for drinking water
- GICE, targeting simpler, lighter and better-performing ice protection systems for aircraft

HIGHLIGHTS FROM 2020

The SafeGraph team studied the work of the four Spearhead Projects described above, and identified the regulatory issues and types of assessments required to ensure both human and environmental safety.

SUSTAINABLE DEVELOPMENT

SafeGraph will provide safety and regulatory results that can be referred to in the future, potentially reducing the need for further experiments and thus reducing waste. Furthermore, this could pave the way for more products based on graphene and layered materials to reach the market.

TOWARDS MARKET-READY RESULTS
SafeGraph will produce four complete dossiers describing experiments, regulatory affairs and risk assessment requirements for aircraft, water treatment, wearable devices and sensors.

PARTNERS
EMPA, Switzerland
University of Trieste, Italy
University of Castilla La Mancha, Spain
University of Natural Resources and Life Sciences, Austria
Chalmers Industriteknik, Sweden

LIMITLESS LAYERS, LIMITLESS POSSIBILITIES

Discover the growing potential of graphene and layered materials

It all began with a chunk of graphite and some sticky tape. Just over 15 years later, this simple – yet adventurous – experiment has led to a vast family of layered materials. Combining them together, like ingredients in a sandwich, opens the door to limitless possibilities.

Graphene is a single layer of carbon atoms, arranged in a hexagonal lattice. Thanks to its peculiar structure, this material exhibits extraordinary properties: it is stronger than steel and even harder than diamond, yet incredibly flexible. Moreover, graphene conducts electricity and heat seamlessly, finding its way into applications from printable electronics and wearable devices to loop-heat pipes: a cooling system used in spacecraft and satellites.

In 2013, the European Commission launched the Graphene Flagship to study its potential and take graphene from the realm of scientific laboratories to the market. Now, after seven years, it has reached cruising speed. The project is stronger than ever – it has created a unique ecosystem that brings together academic institutions, research centres, small companies and leading industries, enabling us to accelerate the time-to-market of graphene and layered materials in an unprecedented manner. Graphene as a technology is mature enough to become part of our lives – and, thanks to the Graphene Flagship's industry-focused Spearhead Projects, European industry will soon adopt these advances and pioneer the next technological revolution.

NEW HORIZONS

Beyond graphene, the Graphene Flagship has driven the discovery of thousands of new materials. Some of them, like hexagonal boron nitride, are also strictly two-dimensional and just one-atom thick. Others, on the other hand, have more complicated crystalline arrangements, which makes them slightly thicker: a good example are transition metal dichalcogenides. Therefore, we often talk about layered materials. However thin, we can always obtain layers of these materials and combine them, like different ingredients in a sandwich. These mixtures are known as heterostructures, and open up a world of possibilities. Among many potential applications, these sandwiches of layered materials enabled ultra-sensitive pressure sensors, miniaturised electronics and memory devices and new systems for separation and filtration.

Understanding all of these different materials will enable a future where heterostructures are designed and prepared on demand. Already, thanks to advances accomplished within the Graphene Flagship, scientists can tailor some of these characteristics and properties – and even scale the synthetic conditions for mass production. Drawing from our experts' understanding of and experience with graphene, our research will continue to expand into the field of layered materials. Graphene Flagship researchers have shown the existence of *at least* 1800 of these ultrathin layers. Just imagine being able to choose from all of these ingredients!

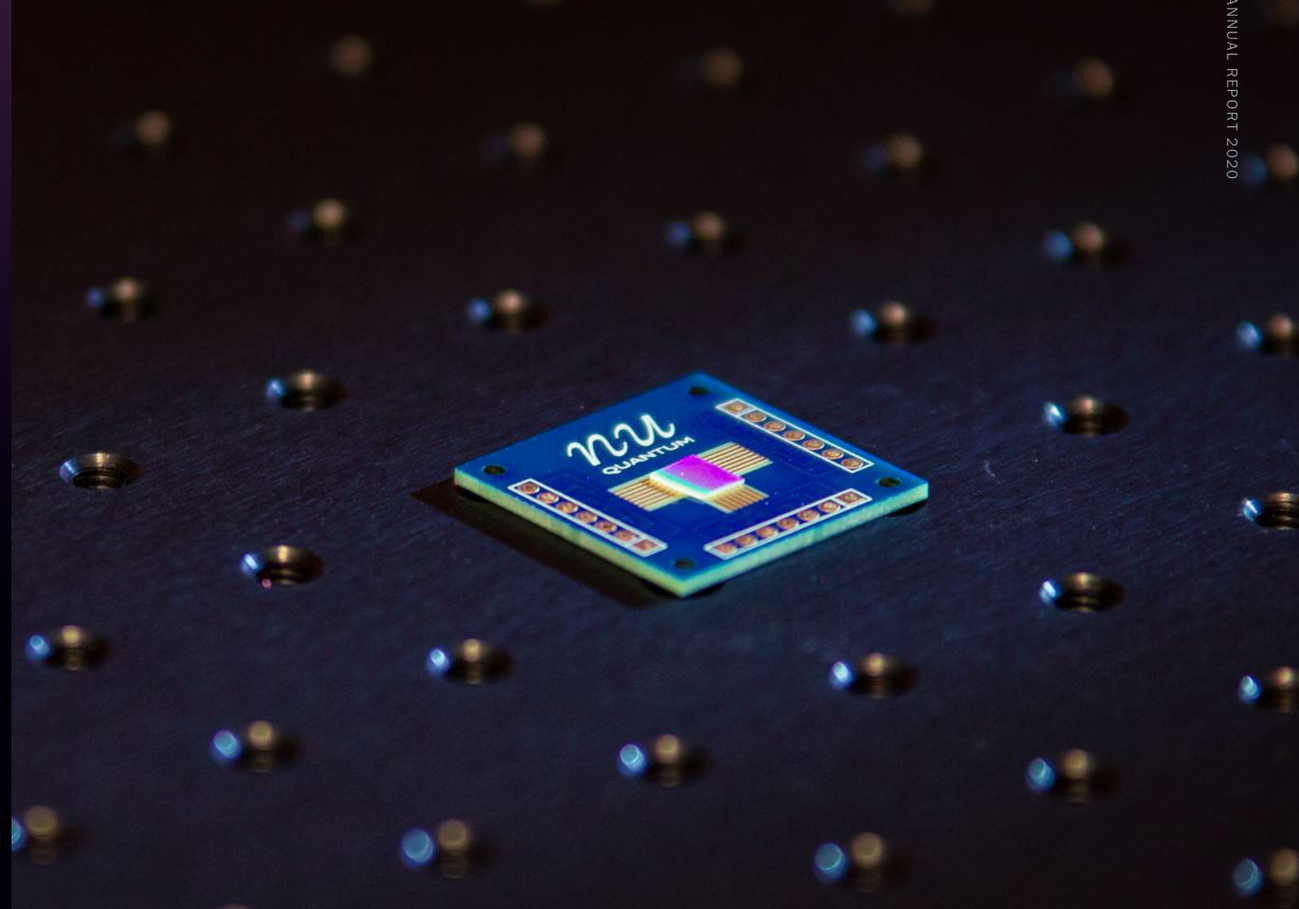
HERE COMES THE TWIST

Beyond just adjusting the composition, altering the angle between the different layers also leads to otherwise unimaginable properties. For instance, two layers of graphene twisted just by 1.1 degrees exhibit superconductivity – a phenomenon that allows flawless electrical conductivity, the free movement of electrons without resistance or heat loss. But slightly modifying this angle leads to completely opposite properties, resulting in total insulation.

This discovery by Massachusetts Institute of Technology's Pablo Jarillo-Herrero, who was an invited speaker at Graphene Week 2018, inaugurated the field of *twistronics*: the study of the properties of layered materials and heterostructures when stacked on top of each other, with a little spin. Since then, this field has expanded the horizons of the Graphene Flagship, particularly our Enabling Science and Materials division. Further discoveries also revealed unexpected magnetic and quantum effects that may pave the way to the next generation of computers and electronics.

Graphene – and the Graphene Flagship – are surpassing peoples' expectations from a few years ago. Thousands of layered materials have been born, new research fields have arisen, and Europe is at the forefront of these new technologies and innovations. All thanks to a tiny piece of tape.

> Already, thanks to advances accomplished within the Graphene Flagship, scientists can tailor some of the characteristics and properties of graphene and layered materials, and even scale the synthetic conditions for mass production."



Graphene has many potential applications in fields like electronics and computing. Credit: Nu Quantum

Enabling Research

Work Package Leader
Vladimir Fal'ko, The University of Manchester, UK

Work Package Deputy
Alberto Morpurgo, The University of Geneva, Switzerland

The Enabling Research Work Package spearheads the scientific progress of the entire Graphene Flagship."

Vladimir Fal'ko
Work Package Leader

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

The Enabling Research Work Package continually furthers our understanding of the physical properties of graphene and layered materials, and their heterostructures, to advance the technology required for device fabrication.

Collectively, these materials encompass a diverse range of properties for a broad range of applications – from conductive to insulating, from transparent to opaque, from diamagnetic to ferromagnetic and from mechanically stiff to flexible. Plus, with the right twist, graphene can even become superconductive.

OUR STORY

Our goal has always been to explore new avenues in fundamental research using graphene and layered materials. This research allows Graphene Flagship scientists to conceptualise new ideas and find new ways of translating fundamental knowledge into applications and products for 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. Together, we investigate new materials and improve the devices and technologies developed at our partner institutions.

OUR RESEARCH

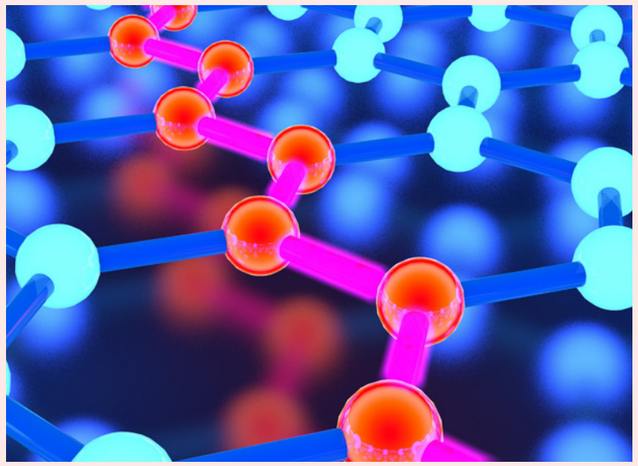
We derive graphene and layered materials from bulk layered crystals. These substances usually have strong covalent bonds within their layers, but only weak 'van der Waals' interactions between them. By combining different atomically thin layers like ingredients in a sandwich, these materials offer the opportunity for Graphene Flagship scientists to create heterostructures – new prototype hybrid materials with multifunctional properties.

HIGHLIGHTS FROM 2020

We would like to highlight two fundamental discoveries in our Work Package. These could lead to the discovery of new types of layered materials for Graphene Flagship researchers and beyond.

Firstly, within the framework of our Work Package, Graphene Flagship partner ETH, Switzerland, developed electrostatically controlled quantum dots using bilayer graphene. They also used quantum dot spectroscopy to analyse and understand the magnetic moments of electrons in the material.

Additionally, Graphene Flagship partner the University of Manchester, UK, created, modelled and characterised twisted bilayers of transition metal dichalcogenides, another type of layered material explored by Graphene Flagship scientists. Twisted bilayers create interesting 'Moiré patterns' that lead to unexpected effects such as magnetism or superconductivity – the ability to transport electricity without resistance.



POWERING THE GRAPHENE FLAGSHIP

The Enabling Research Work Package spearheads the scientific progress of the entire Graphene Flagship. The crux of our research efforts involves identifying or introducing new functionalities, and in turn, this enables the other Graphene Flagship Work Packages and Spearhead Projects to develop new technological applications using graphene and layered materials.

SAILING FORWARD

In Core 3, the current funding phase of the Graphene Flagship, we aim to identify new opportunities and new applications using a broad variety of graphene and layered materials. Moreover, we will combine these in new heterostructures to achieve materials with tailored properties and, hopefully, unprecedented possibilities.

WORKING TOWARDS A SUSTAINABLE FUTURE

The Enabling Research Work Package develops new types of material with functional properties that have great potential for low-power-consuming and low-loss optoelectronics. These could help our society get closer to the European Commission's goal of net zero emissions by 2050, and could form the basis for the next generation of computing and communications technologies in line with the UN's Sustainable Development Goals.

GRAPHENE FLAGSHIP ANNUAL REPORT 2020

Spintronics

Work Package Leader
Stephan Roche, ICN2, Spain

Work Package Deputy
Kevin Garello, imec, Belgium and Spintec, France

Devices fabricated by our Work Package are some of the most sophisticated and complex produced by the Graphene Flagship."

Stephan Roche
Work Package Leader

Expanding the frontier of graphene and layered materials for spintronic devices

The Spintronics Work Package analyses the properties of graphene and emerging layered materials relevant to the field of spintronics, such as strong spin-orbit coupling and magnetic materials. Different combinations of graphene and layered materials will lead to new spin transistors and more efficient low-energy magnetic memory devices (MRAM). To this end, this Work Package fabricates spin devices and optimses their performance, as well as integrating them into current memory technologies.

OUR STORY

The Spintronics Work Package was inspired and supported by Nobel Laureate Albert Fert, who predicted and discovered the phenomenon of spin-related giant magnetoresistance in the early 1980s. This phenomenon gave rise to the spintronics industry, where magnetic sensors for non-volatile memories (MRAM) are used in many commercial computing products.

Over time, spin devices based on graphene and other layered materials have outperformed conventional materials for transferring spin information at room temperature, on an unprecedented scale. These devices could open the door to the design of exceptionally energy efficient memory technologies.

OUR RESEARCH

Non-volatile memory technology is the main target in our sights. This includes most types of computer storage, like hard drives and flash drives. The Spintronics Work Package focuses on using spin-torque phenomena to induce magnetisation reversal and improve memory function – two key factors for the development of new memory technologies.

Furthermore, we continually evaluate how graphene and layered materials can be incorporated into state-of-the-art memories, alongside conventional magnetic materials. These symbiotic technologies are poised for applications in the Internet of Things, neuromorphic computing and high-speed wireless communications.

HIGHLIGHTS FROM 2020

- Our Work Package conducted the first theoretical investigation of spin transport in ultra-clean devices, extending conventional approaches and developing brute force quantum simulations of realistic graphene spin devices
- We demonstrated tunable room-temperature spin galvanic and spin Hall effects in van der Waals heterostructures. These effects enable the conversion of charge current to spin current, and vice versa, which could reduce power dissipation in spintronic circuits
- We found that electrons in bilayer graphene encapsulated by suitable 2D materials can exhibit either exchange or spin-orbit coupling, and the two interactions can be swapped by a gate field. Such exotic heterostructures are very interesting for potential spintronics applications
- We observed a tuneable spin-orbit band gap in graphene for the first time, which could lead to new developments in quantum information transfer.

WORKING TOWARDS A SUSTAINABLE FUTURE

Research and devlopment in spintronics is critical for developing ultralow power memories and future spin-based information processing technologies. By demonstrating that layered materials can further boost the performance of existing memory technologies, we will encourage more innovation and spur development in the field of emerging embedded memories and huge data storage centers.

POWERED BY THE GRAPHENE FLAGSHIP

Collaborations enabled by the Graphene Flagship have positioned Europe at the forefront of research in spintronics. Many aspects of this research, like investigating new materials and developing device fabrication methods, share a common ground with other Graphene Flagship Work Packages. This ecosystem allows us to share information seamlessly: by working together, we speed up our progress.

Furthermore, the Work Package integrates companies and industry-oriented research organisations like Graphene Flagship partners imec, NanOsc, Graphenea and Singulus Technologies, which has been a great stimulation for our fundamental research. The Experimental Pilot Line could further accelerate our breakthroughs and hasten the move towards industrialisation.

SAILING FORWARD

One of our most important goals is to demonstrate that layered materials can be efficiently integrated into magnetic tunneling junction stacks to improve their switching performance in terms of time, energy and cost. This could lead to higher technology readiness level (TRL) developments.

The devices fabricated by the spintronics Work Package are some of the most sophisticated and complex produced by the Graphene Flagship. In collaboration with our partners, we are working hard to solve highly challenging technological issues, like co-integrating layered materials with magnetic materials into the fabrication environment and MRAM technologies.

Above
Scientists from our Work Package in the lab. Credit: Peter Winandy, RWTH Aachen University

Below
The Spintronics Work Package takes graphene from the lab to fab. What does the future hold? Credit: Stephan Roche/ Graphene Flagship

Enabling Materials

Work Package Leader
Mar García-Hernández, CSIC, Spain

Work Package Deputy
Jonathan Coleman, Trinity College Dublin, Ireland

Our objectives have evolved to focus more on the synthesis of more – and better – layered materials, improving their properties, uniformity and reproducibility over large areas."

Mar García-Hernández
Work Package Leader

Developing methods to make graphene and discover new layered materials and heterostructures

The Enabling Materials Work Package develops scalable methods to prepare graphene and other layered materials. When combined like different ingredients in a sandwich, these layers form heterostructures – another of our research interests. Our mission is to develop recipes to produce layered materials in large quantities and export these into production to deliver these new materials, still unavailable on the market, to other Graphene Flagship Work Packages and partners.

OUR STORY

The importance of creating a robust set of processes to develop and produce newly discovered layered materials was recognised very early on in the Graphene Flagship. In the early years of our Work Package, we focused on developing scalable synthesis methods for graphene with properties suitable for a variety of applications.

As time went on, we shifted our focus to other layered materials. We are still committed to improving the quality of large area growth and transfer of graphene. Our focus is now on hexagonal boron nitride (hBN) and transition metal dichalcogenides (TMDs).

We optimise the synthetic methods to make layered materials, and develop new heterostructures that combine them, to provide new device functionalities or improve performance. We continue to explore the large reservoir of new layered materials to find and develop new ones with great potential.

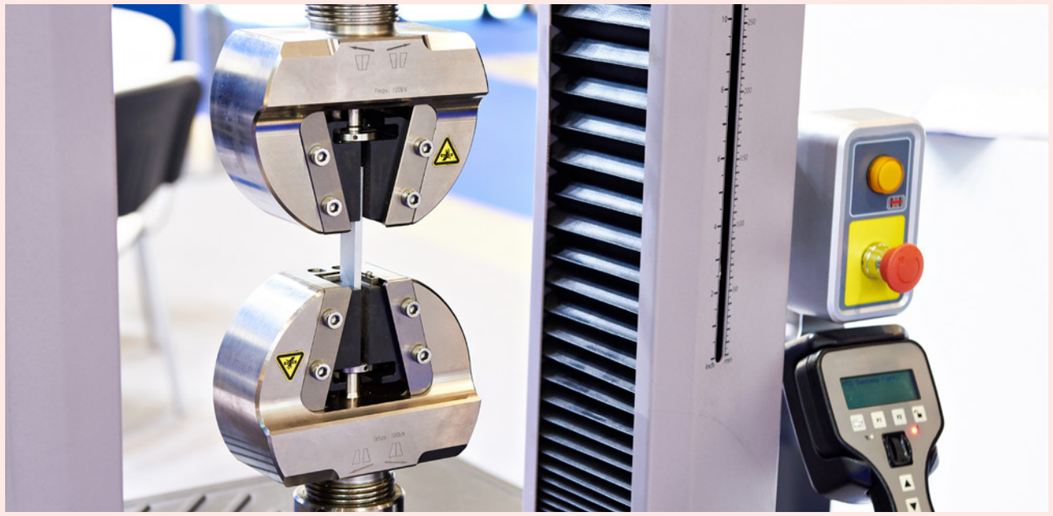
OUR RESEARCH

The Enabling Materials Work Package provides the best graphene and layered materials available. Thus, our Graphene Flagship colleagues can incorporate them into devices and products tailored to their specific applications and needs.

We provide new materials that can be used as cathodes in batteries for the Energy Storage Work Package, and encapsulate large graphene crystals for optoelectronic devices where graphene can exhibit its best performance for the Photonics and Optoelectronics Work Package. We also provide inks with the ideal properties for printed devices, one of the focuses of the Flexible Electronics Work Package, and functionalised graphene specifically designed for biosensing.

HIGHLIGHTS FROM 2020

- Using liquid phase exfoliation, scientists from the Enabling Materials Work Package achieved the synthesis of 2D platelets of non-layered iron pyrite (FeS_2) using liquid phase exfoliation. These are stable in common solvents and can be size-selected and liquid-processed to produce lithium battery anodes with high capacities, approaching 1000 mAh/g
- Together with the Functional Foams and Coatings Work Package, we developed a new class of 2D conjugated metal-organic framework. These materials have been processed as flexible thin films for electrodes in high-performance micro-supercapacitors. Combined with graphene, layered metal-organic frameworks show outstanding cycling stability and have a very high areal capacitance
- We prepared heterostructures of hBN grown on graphene using a lateral epitaxial deposition method. These heterostructures have highly ordered epitaxial interfaces, desirable to preserve graphene's transport properties. The process is industrially relevant, and can be applied to a wide variety of layered materials.



POWERED BY THE GRAPHENE FLAGSHIP

The Graphene Flagship has been key to enabling our research in the long-term, and has fostered many fruitful collaborations between researchers in the consortium. This is the case for most groups in the Enabling Materials Work Package.

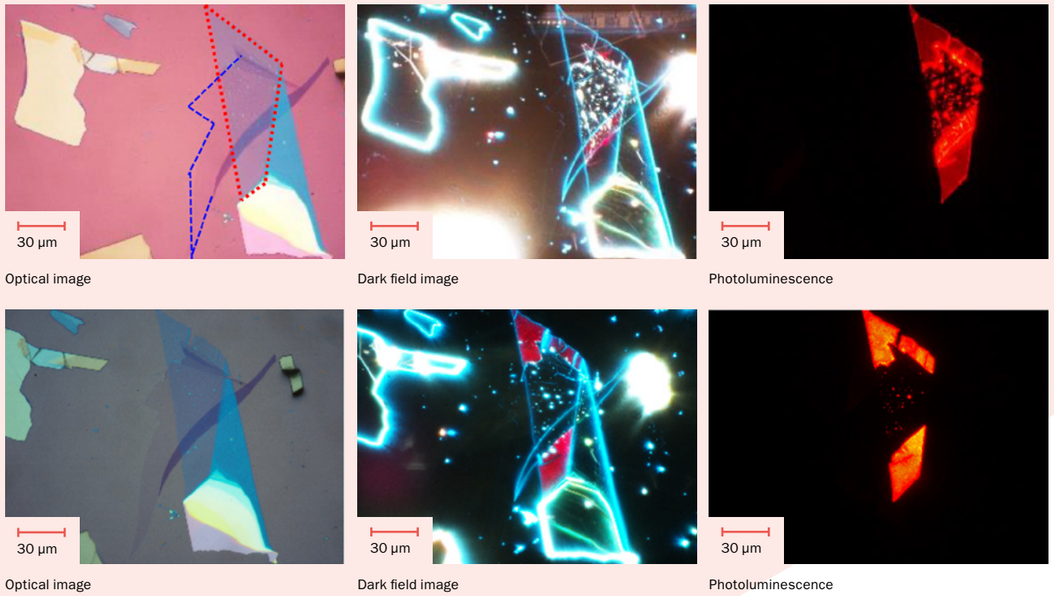
SAILING FORWARD

Now that the Graphene Flagship has sailed into Core 3, our objectives have evolved to focus more on the synthesis of more – and better – layered materials. We are improving their properties, uniformity and reproducibility over large areas, helping the Graphene Flagship progress towards more and more complex architectures.

WORKING TOWARDS A SUSTAINABLE FUTURE

We produce layered materials with outstanding functionalities using very small amounts of raw material. This allows for the miniaturisation of many electronic and optoelectronic devices using few natural resources. By developing high-performance materials for batteries and supercapacitors, we are contributing to the development of greener transportation methods like electric cars.

Images showing the cleaning effects of atomic force microscopy on a silicon dioxide (SiO_2) surface. Credit: James Kerfoot



Optical image | Dark field image | Photoluminescence

Optical image | Dark field image | Photoluminescence

GRAPHENE FLAGSHIP CHARTS ITS COURSE

Our experts are often asked the same question: what happened to the promised applications of graphene and layered materials? Be patient – they are right around the corner.

Graphene followed the classic hype cycle like many up-and-coming technologies, triggered by the first isolation of the two-dimensional material in 2004 and reinvigorated when the 2010 Nobel Prize in Physics was awarded to Andre Geim and Kostya Novoselov. Now, the hype has somewhat subsided. But thanks to the collaborative ecosystem envisioned by the Graphene Flagship, and other international endeavours, graphene is climbing the slope of enlightenment – and it is about to reach full productivity and mass-market penetration.

Since its inception in the early 2010s, the Graphene Flagship has valued the importance of creating evidence-based roadmaps for our technologies. Roadmapping is part of our core research and innovation efforts, providing strategic guidance to achieve our foremost goal: to take graphene and layered materials out of the realm of academic laboratories and into European fabrication lines and market products.

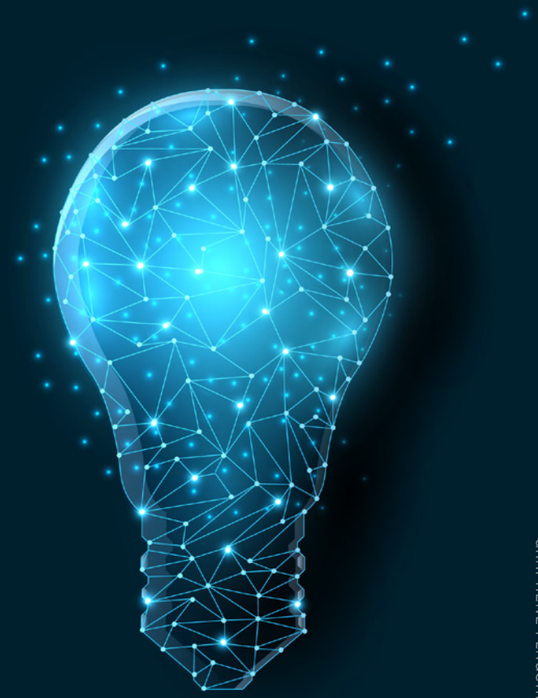
In 2015, we published the first version of the Graphene Flagship roadmap, a gargantuan effort involving more than 60 authors across our many European partner institutions. This publication provided a broad overview of the applications of graphene and layered materials across a variety of sectors, and suggested a series of steps needed to revolutionise the industry. Furthermore, the first Graphene Flagship roadmap offered guidance to achieve a common language for an at-the-time completely new field of materials science. Back then, graphene was just eleven years old, and some definitions, acronyms and even production methodologies were blurry – we needed defined standards to accelerate industry uptake. The roadmap became one of the project's most successful endeavours, and a cornerstone of the field: it has been cited over 2300 times!

> The roadmap provides a broad overview of the applications of graphene and layered materials across a variety of sectors, and suggests the steps needed to revolutionise the industry."

Two years later, we delivered our second roadmap to the European Commission. This new comprehensive study, over 570 pages in total, explores different application areas that show great promise for graphene commercialisation. Some had been known for a while, like the potential of graphene's potential to boost the capacity of batteries and other energy storage devices. But others surprised many readers, like the integration of layered materials into neural interfaces. These new applications are the key to success. The Graphene Flagship roadmap team expanded their horizons and explored a diverse range of ground-breaking research areas and rising industrial sectors.

Now that we have a more complete understanding of the research landscape, we will ensure that graphene and layered materials make a strong impact on the European economy.

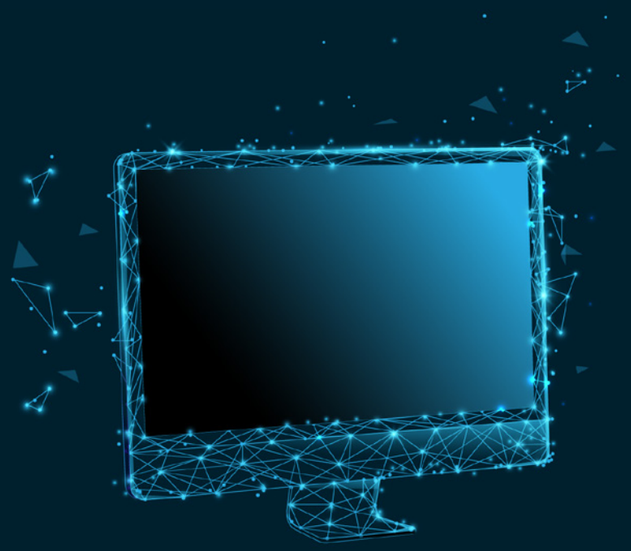
> Beyond energy production, graphene technologies will boost the efficiency of energy storage, enabling the next generation of batteries and supercapacitors."



GRAPHENE FOR ENERGY

Graphene and layered materials have great potential to transform the energy industry. First off, they could revolutionise how we capture solar energy, enabling a seamless transition to a greener, more sustainable future. Graphene boosts the efficiency of solar cells, from dye-sensitised and organic solar cells to newer solutions based on perovskites.

Several projects and research groups within the Graphene Flagship are exploring these synergies, yielding fruitful results like the first graphene-enabled solar farm recently inaugurated in Greece. Beyond energy production, graphene technologies will boost the efficiency of energy storage, enabling the next generation of batteries and supercapacitors. And finally, graphene fuel cells could accelerate the adoption of green hydrogen – a key step towards achieving Europe's climate neutrality goals.

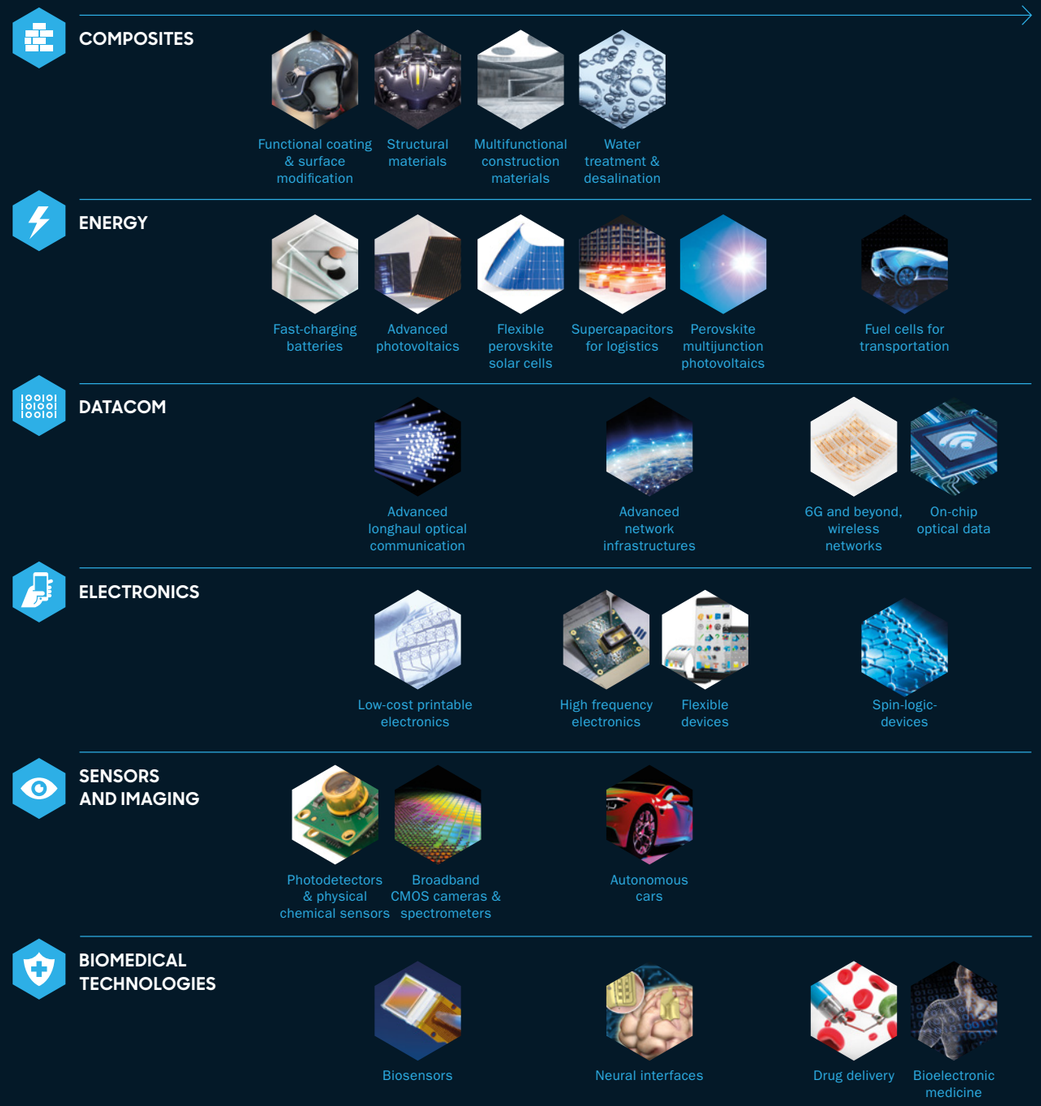


GRAPHENE FOR ELECTRONICS AND PHOTONICS

Silicon electronics are close to their physical limits. Fortunately, graphene and layered materials will unveil new functionalities and applications, pushing our technology way beyond 5G. Graphene showcases unique optical properties. It absorbs wavelengths from ultraviolet to the far infrared, enabling ultra-broadband communications. Moreover, graphene optical devices are tremendously efficient, as they transform almost all light they receive into electric signals. This phenomenon leads to reduced power consumption and maximum efficiency, which comes in handy in a society that keeps demanding higher volumes of data transmission.

Our gadgets are responsible for 4% of greenhouse gases emissions – and experts estimate carbon footprint will keep growing as we attain 30 billion connected devices by 2023. Graphene-enabled devices will reduce the demands of telecom and datacom, leading to more sustainable solutions.

> Graphene and layered materials will unveil new functionalities and applications, pushing our technology way beyond 5G."

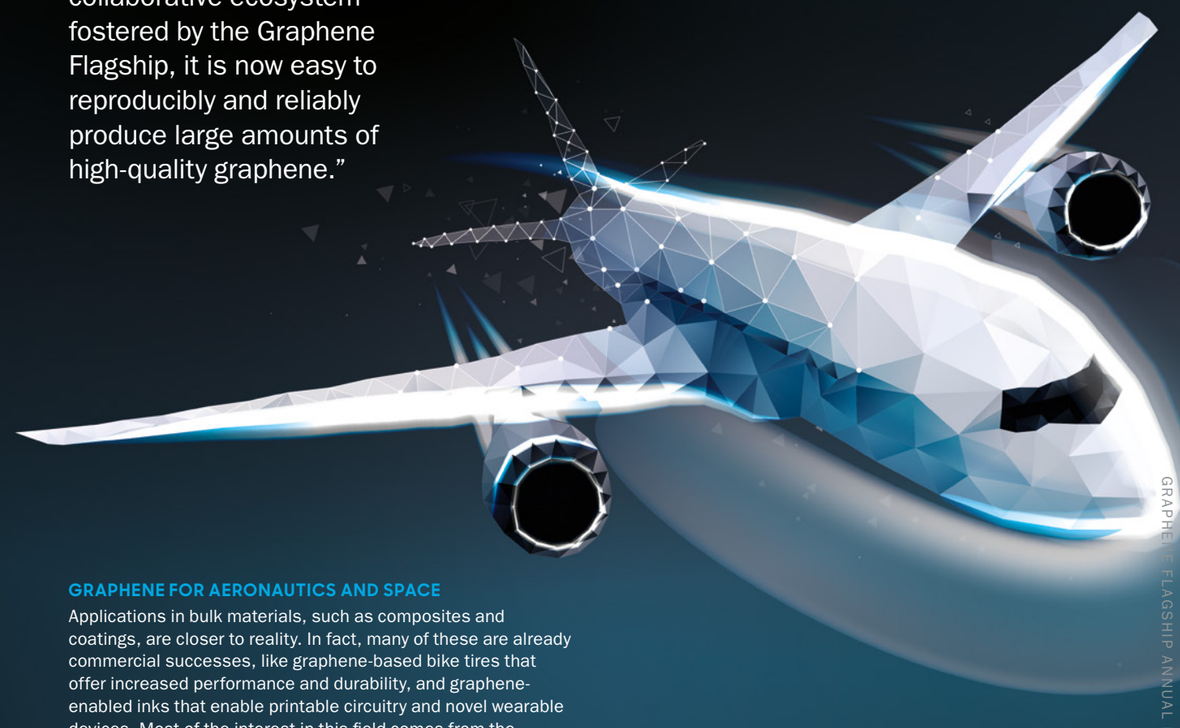


GRAPHENE FOR BIOMEDICAL APPLICATIONS

Two-dimensional and layered materials, like graphene, are very sensitive to changes in their environment. This makes them ideal ingredients for sensors and biosensors, applications that will reach the market in just a couple of years. Further down the line, the possibilities of graphene in biomedical technologies are virtually limitless. Some potential uses include drug delivery, and antibacterial and antiviral materials – which are increasingly important in modern times – as well as biocompatible devices, from protheses and implants to bioengineered tissues and brain sensors.

Predicting market penetration for all of these is quite difficult, as all products must follow pertinent regulatory pathways. But the Graphene Flagship experts are positive: our industrial basis in Europe guarantees the early adoption of graphene technologies in biomedicine. The market potential is indeed positive, as evidenced by the growing interest in Graphene Flagship spin-offs in the biomedical sector, like Grapheal in France and INBRAIN Neuroelectronics in Spain.

Thanks to the unique collaborative ecosystem fostered by the Graphene Flagship, it is now easy to reproducibly and reliably produce large amounts of high-quality graphene."



GRAPHENE FOR AERONAUTICS AND SPACE

Applications in bulk materials, such as composites and coatings, are closer to reality. In fact, many of these are already commercial successes, like graphene-based bike tires that offer increased performance and durability, and graphene-enabled inks that enable printable circuitry and novel wearable devices. Most of the interest in this field comes from the versatility of graphene. It usually enhances mechanical properties – thus increasing shelf life and reducing waste – and, simultaneously, introduces a variety of properties, from electrical and thermal conductivity to the filtration of toxic contaminants.

Probably the greatest potential for graphene-enabled composites appears in the aerospace industry. While adding many functionalities to the materials, graphene also makes mixtures lighter, enabling lighter aircraft and reducing fuel consumption. The Graphene Flagship pioneers several projects and initiatives with leading companies in this sector, such as AIRBUS and Lufthansa Technik, to investigate more sustainable solutions for the future of air travel. Furthermore, our researchers also organise joint activities with ESA scientists to coordinate efforts to understand the possibilities of layered materials for human space exploration. Beyond lighter spaceships, graphene could enable the zero-gravity printing of electronics and batteries, more efficient cooling systems for satellites and self-healing biomaterials to treat astronauts in space.

HIGHER QUALITY THROUGHOUT THE VALUE CHAIN

Three years after releasing the latest Graphene Flagship roadmap, our researchers continue to identify new opportunities for commercialisation. These efforts are key as the innovation landscape is constantly changing. For instance, the demand for graphene has almost quadrupled in the last couple of years. Thanks to the unique collaborative ecosystem fostered by the Graphene Flagship, it is now easy to reproducibly and reliably produce large amounts of high-quality graphene, showing that manufacturing is mature enough to yield mass products.

European industry will soon be ready to absorb and implement the latest innovations in the field, and start manufacturing graphene-enabled batteries, solar panels, electronics, communication devices and medical technologies. The Graphene Flagship roadmap team expects broad market penetration by 2025, creating a paradigm disruption equivalent to steel during the industrial revolution and silicon in our own digital era. Graphene introduces quality and advantages throughout the value chain, all the way from new materials and individual components to innovative products and connected devices.

The Graphene Flagship roadmap brings the research and industrial communities closer together, establishing an understanding of what they need from each other and cultivating effective communication and collaboration. These comprehensive market studies will pave the way to broader applications of graphene and layered materials across different industries. Soon, these materials will be ubiquitous. We are living in a revolution, and we will all witness the transformative power of graphene.

GRAPHENE FLAGSHIP ANNUAL REPORT 2020

Health and Environment

Our investigations study both acute and chronic exposure to different cellular models, and the results we obtain are fundamental for the future of the Graphene Flagship.”

Maurizio Prato
Work Package Leader

Work Package Leader
Maurizio Prato, University of Trieste, Italy

Work Package Deputy
Alberto Bianco, CNRS, France

Assessing the safety and environmental impact of graphene and layered or two-dimensional materials

In the Health and Environment Work Package, our main objective is to assess the safety of graphene and other layered or two-dimensional materials in relation to their use and manipulation. To do this, we investigate any potential risks to health and the environment across all Graphene Flagship Work Packages and Spearhead Projects.

We believe that the comprehensive evaluation of the impact of layered or two-dimensional materials is vital for the protection of human health and the environment, as well as to secure the future applications of graphene and layered or two-dimensional materials, both within the Graphene Flagship and beyond.

OUR STORY

The first and second phases of the Graphene Flagship project, Core 1 and Core 2, laid the foundations for the full safety evaluation of graphene and layered or two-dimensional materials. In 2018, we released a comprehensive review article reporting current knowledge of graphene’s health and safety. It contained a thorough analysis of the interactions of graphene and other layered or two-dimensional materials with different types of cells and organs, and formed the basis for further studies into health and safety.

Overall, our investigations study both acute and chronic exposure to different cellular models, and the results we obtain are fundamental for the future of the Graphene Flagship.

OUR RESEARCH

Our Work Package provides information fundamental to the production of safe materials. In particular, we focus on the study of the interaction of graphene and layered or two-dimensional materials with natural barriers. Furthermore, we study new production methods that are greener and more sustainable.

We are also investigating composites and fragments of materials, as well as the effects of material decomposition and factors relating to a material’s lifetime. These studies are vital to understand for which applications graphene and layered or two-dimensional materials are in accordance with the OECD regulations on safety.

HIGHLIGHTS FROM 2020

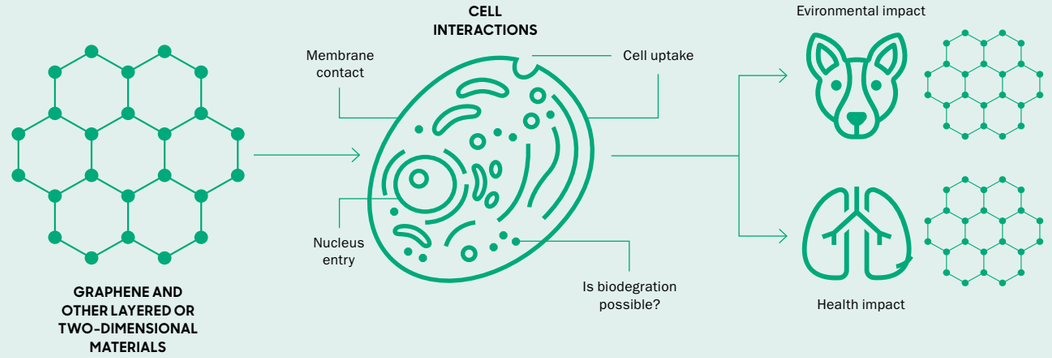
We characterised graphene’s interactions with the skin, its size-dependent interactions with the lungs, and published many studies into the interactions between graphene and natural barriers.

One of our most important accomplishments over this unusual year was to see partners of our Work Package join the Graphene Flagship COVID-19 Working Group. It is encouraging to see how our work can help in the worldwide collaborative efforts to mitigate the effects of pandemics such as COVID-19. Expanding our studies into new potential applications of graphene-based technologies to protect people from the virus, and products to help improve the human way of life and the world around us, make us proud to be part of the Graphene Flagship family.

WORKING TOWARDS A SUSTAINABLE FUTURE

Our studies are fundamental for the green future of graphene and layered materials. New products from the Graphene Flagship need to be safe before they can enter the market: this is a vital step that is entirely contingent on our Work Package.

For instance, we recently found that graphene is biodegradable by human enzymes and in zebrafish. These results represent the first steps towards biodegradable-by-design graphene materials.



POWERED BY THE GRAPHENE FLAGSHIP

Collaboration is key, and the importance of our studies spans the entire consortium. We work with many other Work Packages and partners to assess the safety profiles of materials and products generated by the Graphene Flagship. For instance, data on the neurotoxicity of graphene materials enabled our Biomedical Technologies Work Package to study the use of graphene oxide to treat diseases like Parkinson’s and anxiety.

We also tested materials for our industrial partners, like Graphenea, Grupo Antolin and BeDimensional, to make sure they are safe. Furthermore, we used reduced graphene oxide from partner company Avanzare to study a composite material developed by our Composites Work Package, demonstrating the sheer degree of interconnectivity fostered by the Graphene Flagship.

SAILING FORWARD

Our next steps are to focus on implementing OECD guidelines for graphene and layered or two-dimensional materials. We are investigating ways to obtain safe-by-design functional materials. We plan to develop a library of robust, verified assays that can be used by researchers, not just experts in the field, to determine the impact of their research or products on human health and the world around us.

Biomedical Technologies

Work Package Leader
Kostas Kostarelos, The University of Manchester, UK and ICN2, Spain

Work Package Deputy
Serge Picaud, Sorbonne University, France

Now we are performing the first in-human clinical trials of graphene-based neural interface devices. We are at the cutting edge of this technological field."

Kostas Kostarelos
Work Package Leader

Developing technologies to treat neurological diseases like epilepsy and Parkinson's

In the Biomedical Technologies Work Package, we design devices to manage diseases of the central nervous system, all based on various types of graphene and layered materials. We develop flexible graphene-based devices to record brain activity and explore our technologies for the treatment of blindness, epilepsy and Parkinson's using pre-clinical disease models.

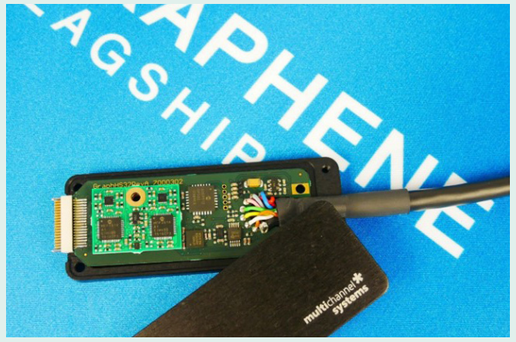
We worked with our industrial partners to launch two commercial products by the end of the Core 2 phase of the Graphene Flagship. This is a great achievement, as the Graphene Flagship roadmap predicted applications in medical technology by 2023 to 2024. In addition, we are now performing the first in-human clinical trials of graphene-based neural interface devices. These activities show that our Work Package is at the cutting edge of this exciting technological field.

OUR STORY

Our Work Package was established three years after the Graphene Flagship's inception. Initially, the Graphene Flagship focused more on physics and materials, so graphene's biomedical applications came along a bit later. However, the great potential of graphene and layered materials for next-generation medical technologies became evident very early on. So, in 2016, the Graphene Flagship launched the Biomedical Technologies Work Package.

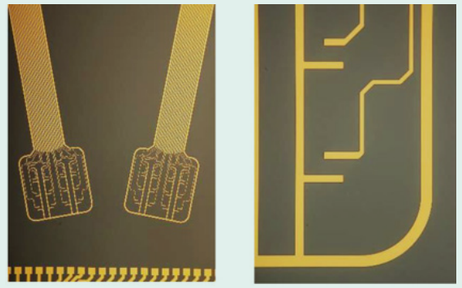
In these four years, our Work Package focused on investigating several graphene and layered material-based applications in the central and peripheral nervous system. Our goal was to identify the most promising applications of these materials in the field.

In Core 3, our focus is to further raise the technology readiness level (TRL) of our devices for selected, targeted areas, ensuring they are adopted by clinics and industry. To reach this goal sooner, we work closely with a Business Developer focused exclusively on this field. The Graphene Flagship's industrial and clinical partners are becoming increasingly important for Biomedical Technologies.



Commercially available neural headstages which amplify, record and analyse data from the brain in vivo, developed by Multi Channel Systems within the Biomedical Technologies Work Package.

WORKING TOWARDS A SUSTAINABLE FUTURE
The scientific output of our work Package directly contributes to the UN's Sustainable Development Goal 3: ensuring healthy lives. Furthermore, through our conscious and ethical hiring, purchasing and waste disposal practices, we also ensure that our research meets SDGs 5, 8 and 12: for gender equality, sustainable economic growth and sustainable production.



Commercial headstages – devices which amplify, record and analyse data from biological systems in vivo – developed by Multi Channel Systems within the Biomedical Work Package.
Credit: Multi Channel Systems

ON THE ROAD TO COMMERCIALISATION
Partner company Guger Technologies, Austria, developed a biosignal amplification and acquisition system that enables recording from graphene transistors. The device has a TRL of 7, meaning their prototype has been demonstrated in an operational environment.

Multi Channel Systems, also a Graphene Flagship partner, used graphene-based neural probes and headstages to develop headstages: all-in-one solutions for amplifying, recording and analysing data in living organisms or cells. The devices have a TRL of 8, showing that the devices are complete and qualified. They plan to market the devices in 2021.

OUR RESEARCH

The applications of our research in the field of neuroscience are already moving forward. For instance, two industrial partners of our Work Package, Multi Channel Systems GmbH, Germany, and Guger Technologies OG, Austria, launched commercial products developed within our Work Package.

Now, we aim to design graphene-enabled sensors that record seizures in patients with epilepsy. Together with our partners ICN2 and ICREA, we launched our spin-off company INBRAIN Neuroelectronics, which will use this graphene-enabled technology to detect seizures moments before they happen, with greater precision than current technologies.
In addition, we are investigating how graphene can improve the electrical stimulation of neuronal circuits to rehabilitate patients with blindness or Parkinson's. This technology could open the door to brain-machine interfaces that reintroduce lost brain function.

HIGHLIGHTS FROM 2020

We launched the first graphene-based neural interface device, in collaboration with our partner Multi Channel Systems, aimed at the neuroscience market. This development will allow neuroscientists around the world to use graphene for their own research, and lead to new discoveries about the human brain beyond the scope of our project.

An additional and remarkable accomplishment during such a challenging year was the creation of INBRAIN Neuroelectronics, a new start-up company. INBRAIN uses licensed technology owned by ICN2, ICREA and the University of Manchester, all three of which are partners of the Graphene Flagship. Furthermore, INBRAIN also recently joined the Graphene Flagship as a full partner.

POWERED BY THE GRAPHENE FLAGSHIP

Our technologies have all significantly benefited from the synergy with other Work Packages enabled by the Graphene Flagship. We all belong to the same large consortium, meaning we can easily communicate with each other, sharing know-how, results and more. In this way, our close interactions with other teams working on materials, electronics and industrialisation have accelerated the maturity of our Work Package's technology.

SAILING FORWARD

In Core 3, our objectives have advanced considerably – to the point that several companies are now involved with commercialising our graphene-enabled products, or commencing investigations in clinical settings. In a few years, we are pleased to have achieved many of our short-term goals.

But our ambitious long-term objectives, like using electrical stimulation to rehabilitate patients, will require long-term studies to assess safety and efficacy. These technologies are poised to be included in medical devices expected to last several decades, so it is important for them to be safe and durable. Therefore, in this funding phase, we expect to provide proof-of-concept devices ready to enter clinical trials. These studies will also provide highly valuable information on graphene's performance in a real clinical setting.

GRAPHENE FLAGSHIP ANNUAL REPORT 2020

Sensors

Work Package Leader
Peter Steeneken, TU Delft, The Netherlands

Work Package Deputy
Sanna Arpiainen, VTT, Finland

We will show that our graphene nanosensors outperform commercial microsensors in all aspects, and that they can be reliably manufactured at high volumes, for a competitive cost."

Peter Steeneken
Work Package Leader

Designing and fabricating sensors based on graphene and layered materials

The mission of the Sensors Work Package is to take advantage of graphene's unique properties to develop new sensing materials and devices. In particular, we are mostly interested in sensors based on nanoelectromechanical systems (NEMS), a class of device with dimensions in the nanometer range – 100,000 times thinner than a human hair.

OUR STORY

NEMS sensors measure changes in forces. As Newton taught us, one needs motion to detect motion. For this reason, moving parts are essential for NEMS sensors. Currently, the industry standard is MEMS sensors, based on *micro*electromechanical systems, which are thousands of times bigger than nanomaterials. Billions are produced every year for devices like mobile phones. MEMS are made using methods similar to semiconductor electronics, with low production costs, and this has led to their widespread commercialisation.

NEMS are smaller – on the nanoscale – and they can provide higher sensitivities. Many NEMS sensors can be combined in an array the same size as a single MEMS sensor, meaning the same surface now opens up possibilities for many new functionalities. Furthermore, NEMS sensors require smaller quantities of materials, reducing manufacturing costs. Graphene nanosensors enable unprecedented capabilities, like counting individual molecules, and the applications of graphene and layered materials in the field of sensing are broad.

OUR RESEARCH

Graphene is only one atom thick, and thus it is the smallest possible NEMS device. We take advantage of its mechanical properties, like its flexibility, to develop high-performance pressure sensors, microphones and accelerometers. This is because graphene's thinness makes it extremely sensitive to changes in external stimuli, such as mechanical force.

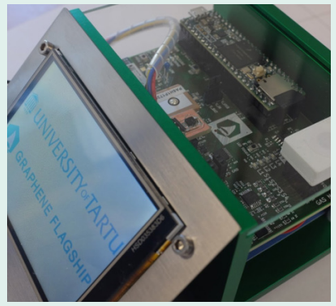
At the same time, graphene sensors are very robust, due to the high in-plane mechanical stiffness and deformability. We can tension a graphene layer like a guitar string, 'tuning' it to detect different things. Thanks to current advances in engineering, we can modify graphene's stiffness and spring constant until it fits within our desired values for detection. We also take advantage of its high electrical conductivity to detect changes in electrical actuation, and to deliver electrical signals for the readout of our sensors.

Although pristine graphene is impermeable to gases – which is essential for pressure sensors – we can create very small pores to make it permeable, or semi-permeable, for certain gases and liquids. This porous graphene enables new sensing functions. Fluids permeate this type of graphene faster than other types of thicker membranes, which we use to create quicker and more energy efficient devices for sensing and separation.

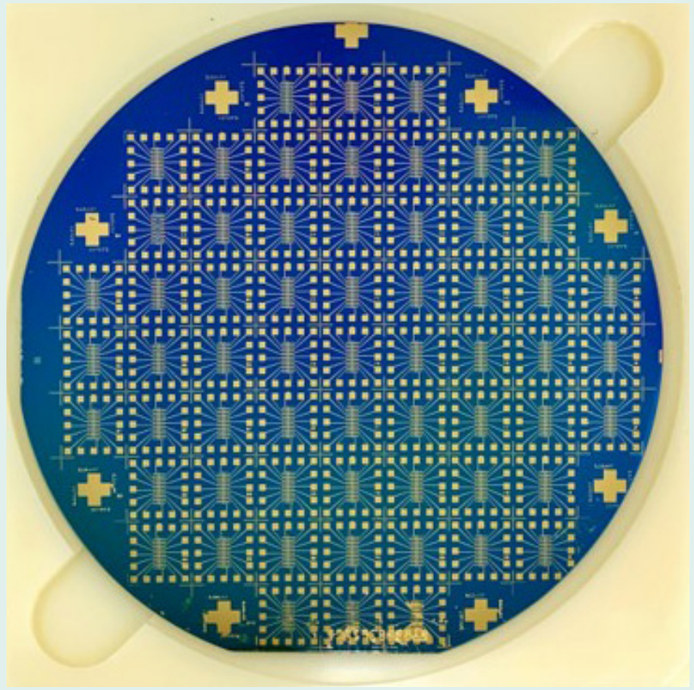
WORKING TOWARDS A SUSTAINABLE FUTURE

Graphene-based sensors can be used to generate data on environmental pollutant concentrations, to create pollution maps so we can easily visualise air quality. They can also be integrated with water supplies and exhaust systems to provide point-of-use quality monitoring.

Furthermore, integrating graphene sensors into the food and farming sectors could help farmers to monitor growth conditions and improve crop yields or reduce energy usage.



Graphene-based air sensor to monitor toxic substances like exhaust gases in the ambient air, and recommend alternate travel routes with cleaner air. Credit: University of Tartu



2D transition metal dichalcogenides (TMDs) are promising candidates for selective gas sensing. Integration onto with silicon-based chips is a prerequisite for high volume fabrication. We demonstrated parts per billion-level sensitivity with a direct low power read out at short exposure times. Credit: Bundeswehr University Munich

HIGHLIGHTS FROM 2020

We covered graphene with thin layers to create new types of gas and biosensor based on NEMS technology, which we showcased in an article published in the journal 2D materials. We also published a comprehensive review article highlighting the effectiveness of graphene and layered materials for sensors based on NEMS.

POWERED BY THE GRAPHENE FLAGSHIP

The Graphene Flagship catalyses many close collaborations, both within and outside our Work Package, that enable us to exchange samples and materials, and produce joint publications with other Graphene Flagship partners, Associated Members and Partnering Projects.

Over the last seven years of the Graphene Flagship, we investigated and developed a range of graphene-based NEMS sensors, including several types of pressure and gas sensors, and the first ever NEMS accelerometer. These devices are key in navigation, medical technologies and consumer electronics. Our Sensors Work Package played a very significant role in this breakthrough, enabled by the Graphene Flagship ecosystem.

SAILING FORWARD

We showed that graphene NEMS sensors can outperform commercial MEMS sensors on various fronts: smaller is better! Now, we need to progress towards industrialisation. We will demonstrate that our graphene sensors outperform commercial MEMS sensors across the board, and that they can be reliably manufactured at high volumes for a competitive cost. For low-volume, high-end products, we anticipate that graphene-enabled NEMS sensors will enter the market in less than five years.

ON THE ROAD TO COMMERCIALISATION

Our first goal is to ensure that graphene-enabled products break into a few high-end markets. This requires reliable proof-of-principle demonstrations that our production and devices outperform existing products.

This was the case for MEMS pressure sensors: they were first demonstrated before 1980, but only started to see market traction during the early 2000s, when they became commonplace in mobile phones.

DIVERSITY MATTERS

Nourishing an inclusive consortium on the road to a bright future

Diversity opens the door to a broader range of talent, encouraging the sharing of new ideas and experiences, and providing insight into the needs and motivations of an increasingly multicultural world. For these reasons and more, the Graphene Flagship recognised the true value of diversity from the very beginning.

INCLUSIVE FROM THE START

Our diversity-positive attitude is reflected by our *Women in Graphene* initiative – a series of events tailored to women scientists in the Graphene Flagship. *Women in Graphene* ran every year and sought to encourage women and girls to study and work in science. Featuring exciting talks from prominent women inside the Graphene Flagship, like Annick Loiseau and Mar García-Hernández, as well as external speakers like researcher and Wikipedia editor Jess Wade and the European Commission's Emelie Kletcha, the initiative ran from 2015 to 2020 and was very well-received. We considered it a resounding success.

But in 2020, we decided that our initiative had the potential to be even more inclusive. So, in April of the same year, we expanded and rebranded Women in Graphene to become *Diversity in Graphene* – a broader initiative to celebrate diversity, build a welcoming community and raise awareness for all underrepresented groups in all STEM fields, but in particular those in the graphene and layered materials community. Notably, *Diversity in Graphene* continues to support gender diversity and commemorates the many achievements of our women scientists.

Diversity in Graphene was launched at the Graphene for Research, Innovation and Collaboration event in September 2020 during a session entitled 'Diversity brings us together' – the Graphene Flagship's most-attended diversity event, with 130 attendees from over 30 countries. The session also featured a talk from Anne Goldberg, member of the Graphene Flagship's Strategic Advisory Council, on women's perspectives in materials science, alongside a panel discussion.

MAKING STRIDES

Diversity in Graphene includes an annual career event in March and a networking event during the annual Graphene Week in September. We created a mentoring programme to connect emerging underrepresented scientists with established ones

> Our diversity-positive attitude is reflected by our *Women in Graphene* initiative – a series of events tailored to women scientists in the Graphene Flagship. Women in Graphene ran every year and sought to encourage women and girls to study and work in science."

in the Graphene Flagship, to foster personal development and growth in our younger generation. We also set up an advisory group to further discuss related issues and strategies to promote diversity.

Furthermore, we strongly encourage diversity in all of our publications: we have dedicated social media channels for *Diversity in Graphene* and a dedicated newsletter. In addition, we also support events from our members and partners, like CARLA, a two-year Horizon 2020 EU-funded project organised by Graphene Flagship partner ICFO to host diverse 'career camps' for underrepresented scientists working on photonics.

> The Diversity in Graphene initiative was publicly launched during the Graphene for Research, Innovation and Collaboration online event on 24 September 2020. With over 130 attendees from across 30 countries, it was the most-attended diversity event in the Graphene Flagship so far."

DIVERSITY GOES DIGITAL

The coronavirus pandemic does not stand in the way of the Graphene Flagship celebrating diversity. Although the in-person 2020 Women in Graphene career event was cancelled to keep everyone safe from the virus, we were quick to come up with an alternative. For the first time ever, we held the Women in Graphene career event in a fully interactive three-dimensional world provided by Virtway Events.

The event saw over 70 attendees, well in-line with our previous in-person Women in Graphene events. The delegates attended talks in the virtual auditorium and chatted with each other in our networking sessions, which aimed to mimic a real-life conference.

Hosting the event online gave us a broader reach than ever, with delegates from as far afield as India joining the fray. Not only this, but students and early-career researchers, who may have otherwise struggled to secure funding for travel and accommodation, were able to join for free from the comfort of their own home.

The speakers included endurance athlete Laura Kennington and prominent women scientists like Katarina Boustedt, original creator of the Women in Graphene initiative. For the first time, we had a student speaker – Bonnie Tsim from Graphene Flagship partner University of Manchester – and Sue Hewitt from Springboard Consultancy led an interactive negotiation training session. We look forward to seeing where the future of digital events takes *Diversity in Graphene*.

Diversity in Graphene gives all underrepresented people – anyone with an interest in graphene, layered materials, the physical sciences or the Graphene Flagship – a platform from which to dive off and explore!

SUPPORTING PERSONAL GROWTH AND DEVELOPMENT

Our all-new mentoring programme, which launched in September 2020, is open to **anyone** involved in the Graphene Flagship – from our Associated Members to our Partnering Projects and the 2D-Experimental Pilot Line. The programme aims to provide new opportunities for networking and improve career prospects by connecting experienced scientists with emerging scientists in the early stages of their career.

We thoroughly train our mentors and strongly encourage them to meet with their mentees on a regular basis. So far, we have paired up around 40 mentors and mentees based on their career aspirations and experience, who will meet monthly over the next year. Sign up for our *Diversity in Graphene* mailing list on the Graphene Flagship website to stay informed about the launch of the next round of mentoring.

Electronic Devices

Work Package Leader
Daniel Neumaier, AMO, Germany

Work Package Deputy
Gianluca Fiori, University of Pisa, Italy

We pursue systems that can function at high frequencies, and take advantage of graphene's properties to create high-performance devices."

Daniel Neumaier
Work Package Leader

Exploiting graphene and layered materials to develop circuits and devices with state of the art properties

The Electronic Devices Work Package aims to take advantage of the unique properties of graphene, and other layered materials, to develop electronic devices and systems with improved performance.

In particular, this Work Package seeks to understand how these materials can be used, in the mid-to-long term, to obtain new functionalities and push the limits of mainstream semiconductor technologies.

OUR STORY

At the very beginning, our Work Package was devoted to technologies based on graphene. But as the project matured, we saw the value of investigating other materials and solutions. For instance, we opted to use graphene for radio frequency (RF) applications and transition metal dichalcogenides (TMDs) for logic devices in programmable circuits.

OUR RESEARCH

We pursue systems that can function at high frequencies, which could pave the way to new technologies like 6G communications. We also take advantage of graphene's properties to create high-performance devices, such as circuits for logic applications like data processing and storage.

Graphene's extreme thinness could also accelerate the development of portable, wearable and flexible devices ideal for the Internet of Things.

HIGHLIGHTS FROM 2020

Our Work Package proudly obtained several exceptional results last year. For instance, we released our first demonstration of a working operational amplifier, which is a fundamental building block for analogue electronics. We achieved this entirely using technology based on the properties of a TMD: molybdenum disulfide (MoS_2).

We were able to create simple electronic circuits on top of a flexible substrate, like paper. This could lead to new types of flexible devices and wearable electronics. To do this, we exploited the dielectric properties of a combination of layered materials: MoS_2 and hexagonal boron nitride.

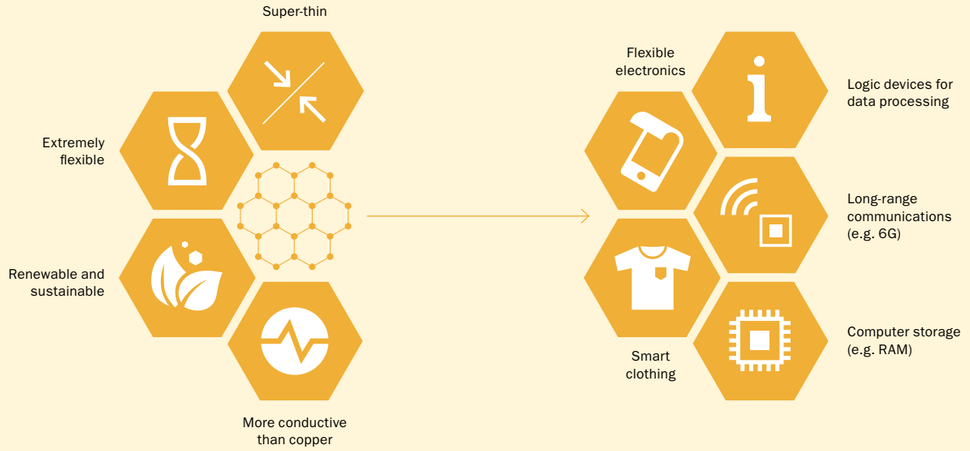
POWERED BY THE GRAPHENE FLAGSHIP

Collaboration enabled by the Graphene Flagship has been key for the success of our Work Package. In particular, we work closely with scientists at other European partners focusing on materials research and production, namely within the Enabling Materials and Wafer-scale System Integration Work Packages. This is crucial for our ultimate goal – the fabrication of high-performance electronic devices.

WORKING TOWARDS A SUSTAINABLE FUTURE

We develop electronic devices that consume less energy, helping to reduce the carbon footprint of electronics and communications technologies. With layered materials like graphene, we can push thin-film transistor technology to become a mainstay in modern day electronics. Next-generation devices could require less energy to operate, and thanks to the thinness of graphene, they could require fewer raw materials to manufacture.

The properties of graphene and layered materials make them ideal for applications in electronics, wearables and communications.

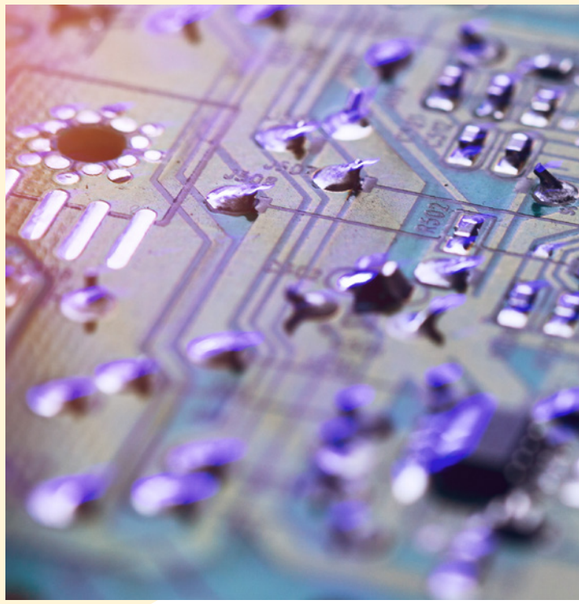


SAILING FORWARD

Now that we have entered the fourth funding period of the Graphene Flagship, we are going to build on the results we obtained in the previous phases. In particular, we will be working hard to further boost our devices' performance, while reducing any sources of defects still present from the fabrication process to improve their yield. In doing this, we will push our technologies ever-closer to industrialisation. Furthermore, another one of our targets is to increase the complexity of integrated devices based on TMDs to improve the functionalities of our circuits.

ON THE ROAD TO COMMERCIALISATION

Our Work Package's main pursuit is to validate our technologies in a laboratory environment: a technology readiness level of 4. We are testing and validating RF circuits for wireless communications, and extract key parameters to benchmark their performance with existing technologies. Then, our industrial partners will test these devices in real environments, driving forward the Graphene Flaship's progress towards marketable products.



Photonics and Optoelectronics

Work Package Leader
Frank Koppens, ICFO, Spain

Work Package Deputy
Andrea C. Ferrari, The University of Cambridge, UK

Industrial partners of our Work Package are crucial to achieving our objectives, as well as our collaboration with the new spin-off companies, CRI, CamGraphIC and Qurv Technologies."

Frank Koppens
Work Package Leader

Using graphene and layered materials for long-range communication, imaging, sensing and analysis

The Photonics and Optoelectronics Work Package studies the effects of light on graphene and layered materials, and combines this with electronics to enable new optoelectronic devices. We create devices that can source, detect and control light for a broad range of applications.

OUR STORY

During the initial 'ramp-up' phase of the Graphene Flagship, we united forces to identify the technological challenges in the field of optoelectronics and determine areas in which graphene could unlock new applications and enhance existing ones.

We initially focused on more fundamental research for optoelectronic components. Thanks to our interactions with key players in industry, participating in leading exhibitions like Mobile World Congress Barcelona, we shifted our focus towards solving specific societal challenges in fields like imaging, sensors and communications.

OUR RESEARCH

Our Work Package develops optoelectronic components based on graphene and layered materials, and integrates them into complete systems, like optical receivers for data communications, image sensing arrays, medical imaging, sensing systems and spectrometers.

In the current phase of the Graphene Flagship, we are working on several prototypes, among others:

- A radio access and optical network prototype to address growing demands for better data transmission technologies, paving the way to 6G technologies
- A coherent Raman microscope prototype with applications in bioimaging, which can improve the early detection of cancer
- A gas sensor to detect volatile organic compounds (VOCs) harmful to human health.

HIGHLIGHTS FROM 2020

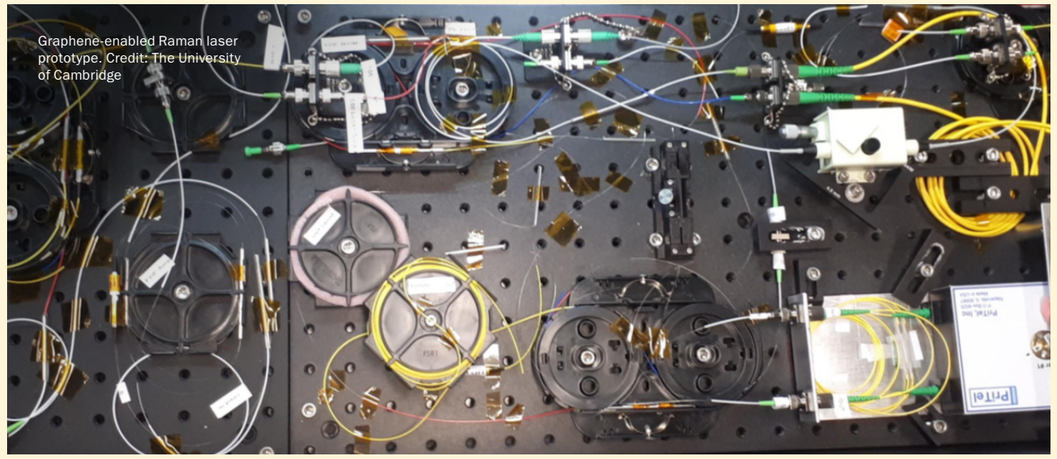
Our Work Package established three spin-off companies with the Graphene Flagship in 2020: CRI and CamGraphIC, in Italy, and Qurv Technologies, in Spain.

We developed graphene photodetectors with sub-nanosecond response times and very high mobility. These could have applications in security, like in airport scanners; in industry, such as for process monitoring; and for measurements in quantum technologies.

We also developed state-of-the-art THz detectors, the fastest, broadest band and lowest noise detectors, working at room-temperature. We engineered miniaturised THz frequency combs, integrating quantum cascade lasers with a graphene saturable absorber-reflector that preserves phase coherence between modes, paving the way to a number of key applications including high-precision tuneable broadband-spectroscopy and quantum metrology.

WORKING TOWARDS A SUSTAINABLE FUTURE

The communications industry causes 2 to 2.5% of all greenhouse emissions, projected to reach 14% by 2040. Graphene can enable more efficient photonic devices with smaller footprints and lower power consumption. In addition, our low-cost broadband spectrometers could increase make crop harvesting more efficient and reduce food waste – and graphene-enabled gas sensors can detect CO_2, NH_3 and some VOCs to monitor air pollution.



Graphene-enabled Raman laser prototype. Credit: The University of Cambridge

Additionally, we used graphene nanoribbons for gas sensing by depositing an ultrathin chemisorbing polymer layer on the surface. They can capture and sense CO_2 with a limit of detection of 390 ppm – the amount of CO_2 in the ambient atmosphere.

POWERED BY THE GRAPHENE FLAGSHIP

The Graphene Flagship is an ideal platform to gather knowledge from top-tier European researchers, and to combine expertise with industrial partners to tackle ambitious challenges that would not be possible to overcome alone. The Graphene Flagship avoids overlapping efforts and ensures that all partners are well-credited for their contributions.

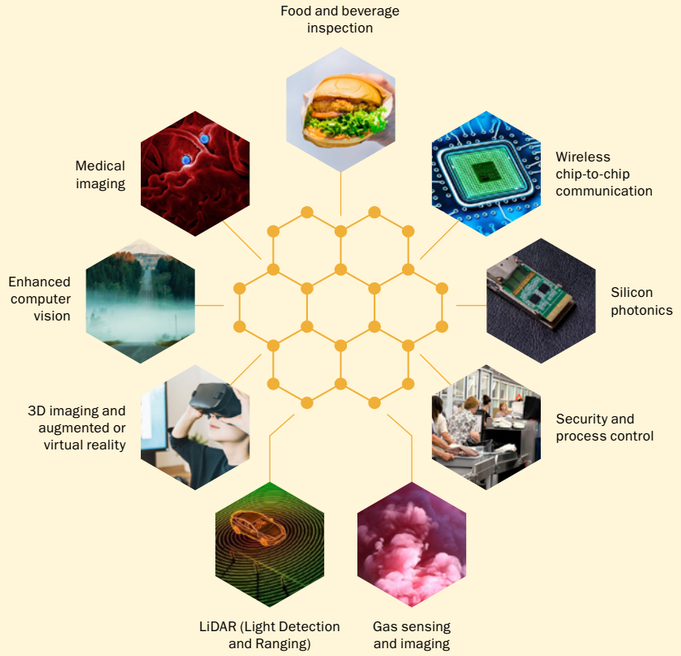
The consistency and sustained funding from the Graphene Flagship allowed us to plan our research for the mid-to-long term, further raising the bar for our developments in opto-electronics.

SAILING FORWARD

We target a variety of optoelectronic applications, from optical networks to plasmonic sensors and broadband detectors. Our work will help the Graphene Flagship progress towards next-generation long-range optical communications on several fronts. We are working with seven companies, including our newly founded spin-offs CRI, CamGraphIC and Qurv Technologies. Industrial partners make up 27% of our Work Package.

We also work on several tasks that will help us perform more exploratory activities, feeding directly into our application-oriented efforts. The perfect balance between these two pursuits will help us to obtain meaningful results that can easily be adopted by industry.

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



ON THE ROAD TO COMMERCIALISATION

CRI aims to commercialise a graphene-based two-colour synchronised laser. With a technology readiness level (TRL) of 4, their system is being validated for real-time tumour imaging in biological samples. It could also help scientists to understand disorders like fatty liver disease.

Qurv Technologies uses image sensors based on graphene and quantum dots developed by our Work Package. They aim to remove the barriers for advanced computer vision technology to be adopted by industry. They also lead the AUTOVISION Spearhead Project, developing sensors for self-driving cars.

CamGraphiC aims to develop new 5G and 6G communication technologies with optoelectronic building blocks based on graphene and layered materials.

GRAPHENE FLAGSHIP ANNUAL REPORT 2020

Flexible Electronics

Work Package Leader
Maria Smolander, VTT, Finland

Work Package Deputy
Henri Happy, The University of Lille, France

We aim to demonstrate the use of graphene in conductive textile fibres, yarns and fabrics, for large-area applications as an alternative to metal-based conductive textiles.”

Maria Smolander
Work Package Leader

New stretchy, conformable electronic devices made of graphene and layered materials

The Flexible Electronics Work Package focuses on developing new classes of flexible, stretchable and conformable electronics, based on graphene and layered materials. We are focusing on the mechanical robustness, conformability, sustainability and non-toxicity of our devices, as well as their potential for cost-efficient large-area production.

OUR STORY

We evolved from the Graphene Flagship’s continuous efforts to study and improve materials, to develop reliable and large-scale manufacturing process, and to validate components and building blocks in working demonstrators.

OUR RESEARCH

We aim to demonstrate the use of graphene in conductive textile fibres, yarns and fabrics, for large-area applications as an alternative to metal-based conductive textiles. These will be useful for products like smart clothing, elastic wearables and flexible touch panels. We are also working on manufacturing graphene and layered material-containing textile fibres with stable electrical or thermal conductivity, using different fabrication methods like screen printing and impregnation.

We are also working on stretchable electronics for devices like smart patches, with a particular focus on physical sensors for strain, stretch and touch based on graphene and layered materials.

We are developing graphene-enhanced electronics for paper-based, disposable smart products, like smart packaging and other connected products. We are also investigating flexible sensor readouts and communication circuits.

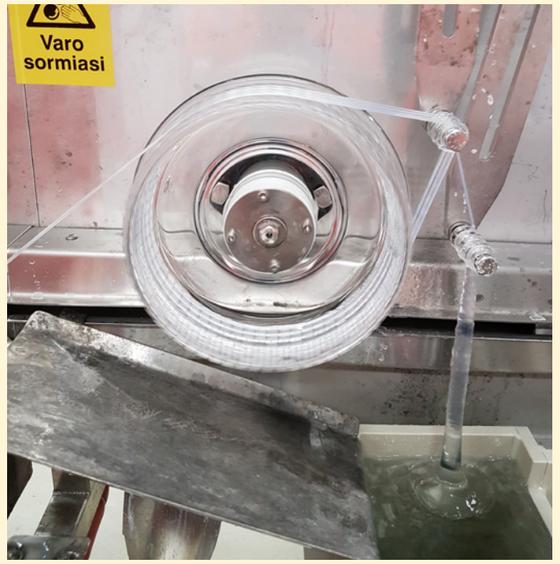
HIGHLIGHTS FROM 2020

We achieved several demonstrators of our products, with technology readiness levels (TRLs) from 2 to 6. Our main results are as follows:

- A washable strain sensor to measure breathing, and a pressure sensor to measure heart rate
- A touch-screen demonstrator based on chemical vapour deposited graphene
- Graphene field effect transistors for radio frequency circuits with 80 to 90% yield and high mobilities of 4500 to 7000 cm^2/Vs
- A molybdenum disulfide field effect transistor with a yield above 95% and a mobility above 10 cm^2/Vs
- Layered material-based printed field-effect transistors for integrated digital and analog electronics on paper
- Progress towards a flexible X-ray sensor array based on a flexible TFT back plane
- We also submitted a new intellectual property for graphene-based electrodes for an electrocardiogram: a medical scanner to image the heart and its blood vessels.

WORKING TOWARDS A SUSTAINABLE FUTURE

Using low-cost materials like graphene with sustainable production methods, we can make greener flexible devices and reduce their environmental footprint. Making flexible devices with printing technology saves energy and materials over conventional methods, and graphene and layered materials could replace some of the toxic or harmful materials widely used in electronics.



Wet-spinning equipment producing cellulosic fibres. Credit: VTT

ON THE ROAD TO COMMERCIALISATION

We achieved eight demonstrators with TRLs between 2 and 6. Our concepts included a wearable autonomous sensor, a touch interface for structural electronics, a paper-based board game, a flexible X-ray detector, a comfortable and capacitive on-textile user interface, and a pair of ‘gaming shoes’ with an electronic interface in the soles. Most of these developments were led by our industrial partners.

POWERED BY THE GRAPHENE FLAGSHIP

As with many Graphene Flagship Work Packages, the Flexible Electronics team needs broad technical expertise and high levels of competence in fields like material synthesis, sensors, circuit design and fabrication technologies. On top of this, we also need experts who can analyse the needs of the market and identify critical business opportunities to help us decide the best way forward.

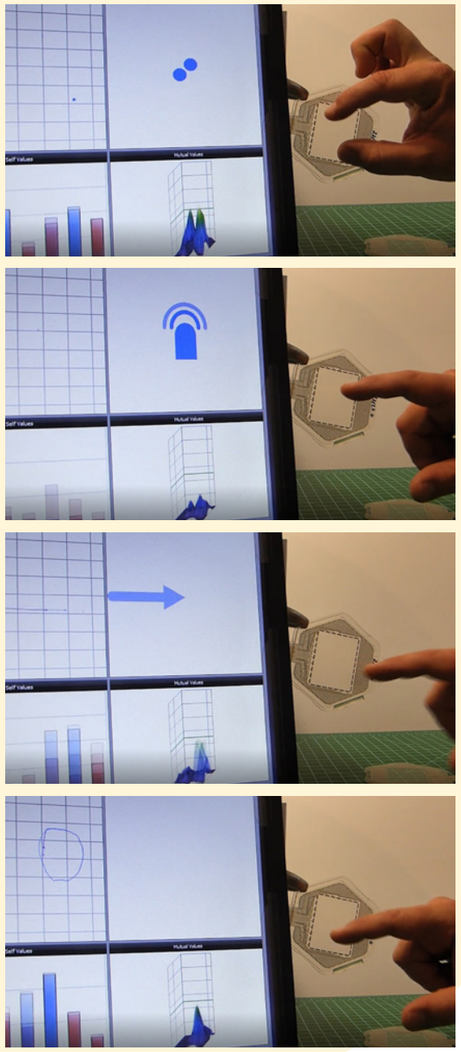
The wide, multidisciplinary network of partners in the Graphene Flagship provides us with the expertise we need. Furthermore, the highly active and collaborative nature of the Graphene Flagship continually supports our developments in flexible electronics.

SAILING FORWARD

Our objective is to demonstrate the viability of graphene and layered materials for flexible electronics applications.

We will achieve this by developing functional prototypes that are more reliable and perform better than the state-of-the-art, or provide advantages in terms of consumer appeal, business appeal or environmental protection. Our strong industrial vision is reinforced through dedicated efforts from our industrial partners, pushing several selected applications with high potential societal impact from the lab to the market.

Our work on graphene and layered material-containing textile fibres, yarns and fabrics is new to the current phase of the project, and two new industrial partners have joined: Trevira and Interactive Wear, Germany.



Sensors developed by the Flexible Electronics Work Package capable of detecting multiple touches, double taps, swipes and even drawings. Credit: CEA

Wafer-scale System Integration

We work towards achieving stable wafer-scale processes, including the growth and transfer of layered or two-dimensional materials, and device fabrication with low levels of metal contamination.”

Marco Romagnoli
Work Package Leader

Work Package Leader
Marco Romagnoli, CNIT, Italy

Work Package Deputy
Amaia Zurutuza, Graphenea, Spain

Integrating graphene and layered materials into silicon fabrication lines

Wafer-scale system integration is the process of building large integrated circuits, on a silicon wafer, from the bottom up. The goal of our Work Package is to develop new methods to integrate graphene and layered materials, and graphene-based microelectronic components, into silicon fabrication lines. This is a crucial step to manufacture the next generation of photonic, optoelectronic and high-frequency devices based on graphene and layered materials.

OUR STORY

Our Work Package was established in the previous phase of the Graphene Flagship, beginning in 2018. We wanted to address the needs of the Graphene Flagship scientists using graphene made with chemical vapour deposition (CVD). CVD is the ideal process to obtain pristine graphene monolayers for applications in electronics and photonics, as well as to integrate graphene production into wafer-scale systems.

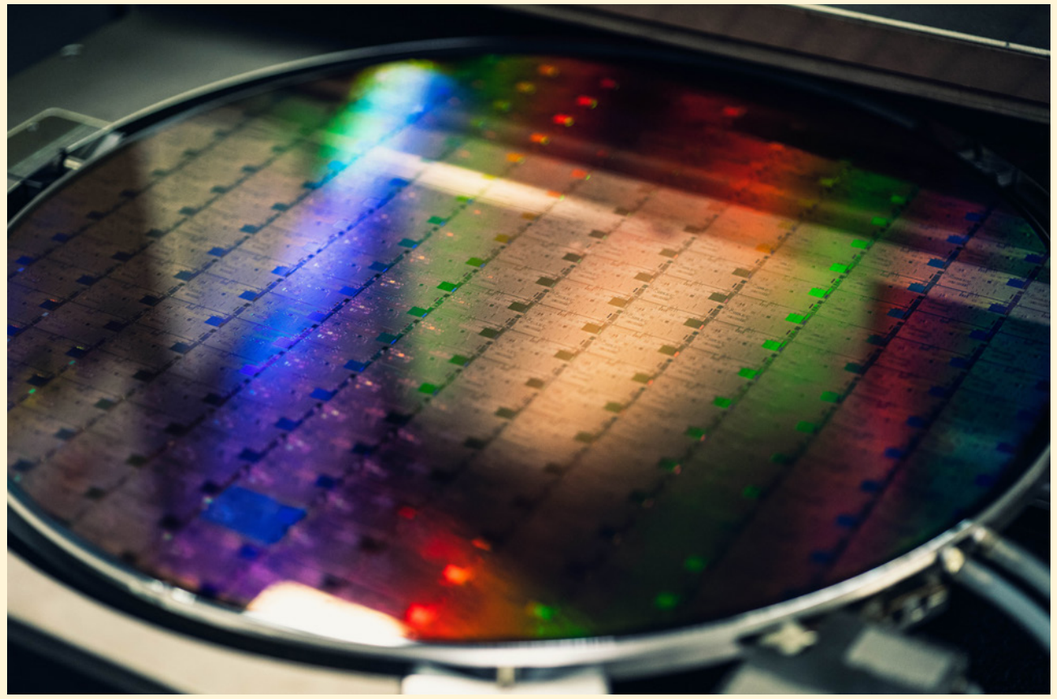
Prior to the inception of the Wafer-scale System Integration Work Package, Graphene Flagship researchers were using CVD-grown graphene in the lab, and the transfer into the fabrication environment was complicated. Now, we have achieved working demonstrations of several wafer-scale electronic and photonic devices made from CVD graphene.

OUR RESEARCH

Our scope is three-fold. Firstly, we develop and grow graphene films on a large area, then transfer them to a silicon wafer, and finally encapsulate them for protection during integration. We also create and improve wafer-scale testing systems, designed to map important graphene parameters, like mobility and conductance, which could further help with graphene’s integration into silicon wafers.

Another objective is to overcome the challenges related to integrating new advanced materials into industrial applications. This could enable a faster industry uptake of graphene and layered materials, and seamless integration into photonics, electronics and optoelectronics applications.

New materials must meet the requirements of industry, such as high yields, low contamination and low process variation for wafer-scale production and device fabrication. Therefore, in our Work Package, we work towards achieving wafer-scale processes that are stable and reproducible, including the growth and transfer of layered materials and device fabrication with low levels of contaminants, such as metals.



Opposite page
A scientist from the Wafer-scale System Integration Work Package holding up a wafer-scale device based on graphene and layered materials. Credit: imec

Above
Our Work Package develops new methods to integrate graphene and layered materials, and graphene-based microelectronic components, into silicon fabrication lines for next-generation computing technologies. Credit: imec

HIGHLIGHTS FROM 2020

In 2020, we obtained very encouraging wafer-level statistics for graphene field effect transistors which met the ‘back end of line’ (BEOL) requirements imposed by the semiconductor industry.

We worked towards integrating more than one type of device onto the same chip, such as photodetectors and modulators together. This is not possible with current materials in the photonics industry – graphene and layered materials could be the answer to true multifunction electronic devices.

POWERED BY THE GRAPHENE FLAGSHIP

The sheer size of the Graphene Flagship, in terms of the number of partners and disciplines covered, and its collaborative approach to science, has provided unique opportunities for scientists across the entire consortium.

Furthermore, the progress in wafer-scale integration triggered the creation of a bigger endeavor focused on integrating graphene and layered materials into the next generation of electronics and semiconductors: the 2D Experimental Pilot Line. This initiative will integrate graphene and layered materials into semiconductor platforms, keeping Europe at the forefront of this technological revolution. Scaling-up manufacturing is a critical step forward for the advancement of electronic components.

SAILING FORWARD

Our final target is to demonstrate methods and tools that permit wafer-scale manufacturability, reproducibility and a high yield. Going forward, we will also investigate other layered materials for wafer-scale integration, like tungsten disulfide, tungsten diselenide, molybdenum disulfide and molybdenum diselenide.

ON THE ROAD TO COMMERCIALISATION

The technology readiness levels (TRLs) of our developments depend on the application.

Our photonic devices for optical communications, like graphene photodetectors and modulators, have TRLs of 5 or 6. This means they have been validated or demonstrated in relevant environments. On the other hand, in the case of certain electronic applications such as wafer-scale GFET matrices or THz absorption spectroscopy, the TRL is approaching 8.

GRAPHENE FLAGSHIP ANNUAL REPORT 2020

FROM LAB TO FAB

Division Leader
Cedric Huyghebaert, imec, Belgium

Deputy Division Leader
Sanna Arpiainen, VTT, Finland

Introducing the Graphene Flagship's new manufacturing facility for graphene-based electronics, optoelectronics and sensors

In October 2020, the Graphene Flagship marked a major milestone toward its commercialisation goals with the launch of the 2D Experimental Pilot Line to integrate graphene and related layered materials into semiconductor platforms. With this new project, the European Commission will invest €20 million in the next generation of electronics and semiconductors.

Graphene and layered materials are ready to hit the market, maturing out of the lab for electronics and optoelectronics applications. The 2D Experimental Pilot Line (2D-EPL) will be the first graphene foundry to integrate graphene and layered materials into semiconductor platforms, keeping Europe at the forefront of this technological revolution. Scaling-up manufacturing is a critical step forward for the advancement of electronic components.

INDUSTRY IN OUR SIGHTS

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

During the EC-supported period, the 2D-EPL will develop the processes and practices needed to produce electronic and optoelectronic/photonic applications based on graphene and layered materials, and after the end of the publicly funded period, these services will continue to be provided on commercial terms.

The Graphene Flagship, a ten-year, €1 billion research initiative by the European Commission, has transitioned into Core 3 and the 2D-Experimental Pilot Line – comprising the fourth funding cycle of the project. In this phase, our target is to advance the commercialisation of graphene and layered materials. The Experimental Pilot Line is a major step towards this goal.

ENCOMPASSING THE ENTIRE VALUE CHAIN

Born within the innovative ecosystem pioneered by the Graphene Flagship, the new 2D-EPL will cover the entire value chain, from tool producers and chemical and material providers to manufacturing lines. This collaborative project will integrate several Graphene Flagship members to pioneer the fabrication of new prototype electronics, photonic devices and sensors integrating graphene and layered materials. The 2D-EPL will offer comprehensive prototyping services to companies, research centres and academics, so they can develop and test their innovative technologies based on layered materials.

We want to offer early access to experimental pilot line production for the innovative graphene community in Europe."

Cedric Huyghebaert
Division Leader

Right
With the launch of the 2D-EPL, the Graphene Flagship now administers two separate European Commission projects that will run concurrently and collaboratively.

"By developing a European pilot line for the processing of graphene and layered materials, we aim to bring these innovative materials from the academic laboratories to the semiconductor production lines, making them compatible with the standards in the industry. Moreover, we want to offer early access to experimental pilot line production to the innovative graphene community in Europe. The pilot line will allow them to scale up the production of their innovative devices based on graphene and layered materials," explains Cedric Huyghebaert, technical leader for the EU-funded 2D-EPL project, and programme manager for exploratory material and module integration at imec, Belgium.

NEW HORIZONS

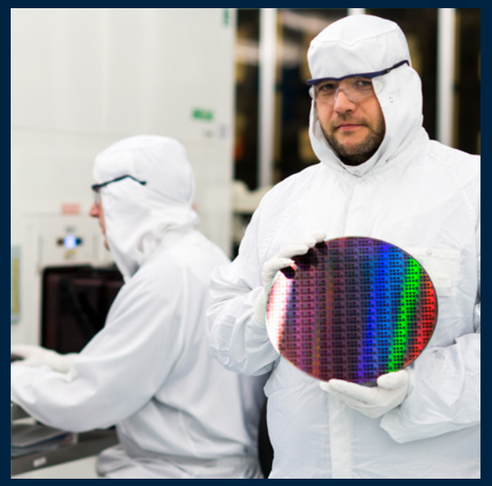
Combining graphene and layered materials with silicon could enhance the potential of electronic technologies traditionally based on silicon. Nevertheless, integrating both materials on a large scale has been challenging, and until now, advances have progressed at a slow pace – mostly due to a lack of infrastructure. The 2D-EPL will address this challenge, allowing manufacturers to control the interfaces between silicon semiconductors and 2D materials on a large scale.

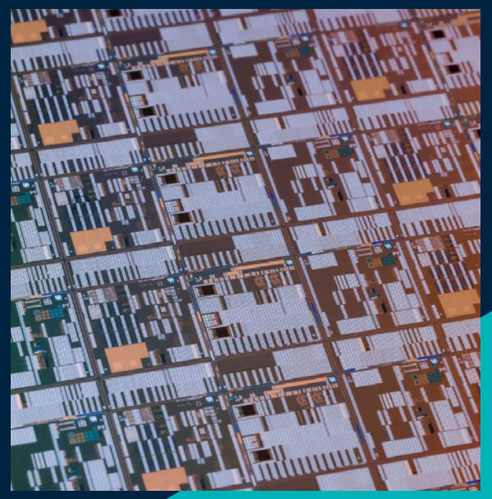
Collaboration between the 2D-EPL and the Graphene Flagship Core projects will be paramount, as a large number of the potential applications supported by the pilot line are under development in the Graphene Flagship core project. Nevertheless, the focus and organisation of the new 2D-EPL project is radically different. Its objective is to build a long-term plan to overcome the 'window challenge' of publicly funded projects, and it will become a sustainable on-demand service for research and innovation in Europe and beyond.

The 2D-EPL will count on expertise from imec, Belgium, which will lead the scientific and technological aspects of the project. The Graphene Flagship team at Chalmers University of Technology, Sweden, will also join the project – providing all of its expertise in management and communication. Moreover, the pilot line will be supported by a core technical steering group consisting of principle investigators from different partners of the project, and it will be overviewed by an Industrial Advisory Board, integrated with key players from the European semiconductor industry.

Below
Wafer production is already ongoing in 2D-EPL partner imec's cleanroom. Credit: imec

Bottom
Integrating graphene and layered materials in silicon wafers could revolutionise the electronics industry. Credit: imec





Energy Generation

Work Package Leader
Emmanuel Kymakis, Hellenic Mediterranean University, Greece

Work Package Deputy
Aldo di Carlo, University of Rome Tor Vergata, Italy

The main focus of our Work Package is to fulfil mankind's energy needs for the cities, industries and transportation methods of the future."

Emanuel Kymakis
Work Package Leader

Making photovoltaic panels and hydrogen fuel cells based on graphene and layered materials

The Energy Generation Work Package develops functional components for photovoltaic panels and hydrogen fuel cells, like electrodes and interlayers, based on graphene and layered materials. The core strategy of our Work Package abides by the following ethos:

- To improve power conversion efficiency
- To extend device lifetimes
- To significantly reduce the use of raw materials, like platinum.

All of this together leads to cheaper manufacturing costs than state-of-the-art technologies, and a lesser impact on the environment.

OUR STORY

The ramp-up phase of the Graphene Flagship focused on using graphene and layered materials for many different photovoltaic and fuel cell technologies. After optimisation, we chose perovskite as the most promising platform for photovoltaics, and demonstrated device scalability with high efficiencies of around 11.6% over an active area of around 0.01 m^2. We also showed that graphene and layered materials with high defect concentrations can boost the performance and durability of fuel cells.

By the end of the previous phase of the Graphene Flagship, we had engineered graphene and layered materials to be very scalable in photovoltaic cells, with high efficiencies of above 14% with an active area of 0.2 m^2. The hallmark of this progress was the design, construction and operation of the solar farm in Crete, Greece.

We also developed and integrated low-platinum, durable fuel cell electrodes, enabled by graphene and layered materials, into devices with large active areas (over 0.02 m^2) and outstanding specific power values (19 kW per gram of platinum). These values exceed the performance of the state-of-the-art.

OUR RESEARCH

There is a huge demand for breakthroughs in the formulation of materials that can enable large-scale energy conversion technologies for sustainable energy generation. Furthermore, the rapid onset of Internet of Things technologies demands high-power smart devices and portable energy sources with high energy and power density.

The main focus of our Work Package is to fulfil mankind's energy needs for the cities, industries and transportation methods of the future. Novel photovoltaic and fuel cell technologies improved by graphene and layered materials will play a crucial role in the fulfillment of these needs.

HIGHLIGHTS FROM 2020

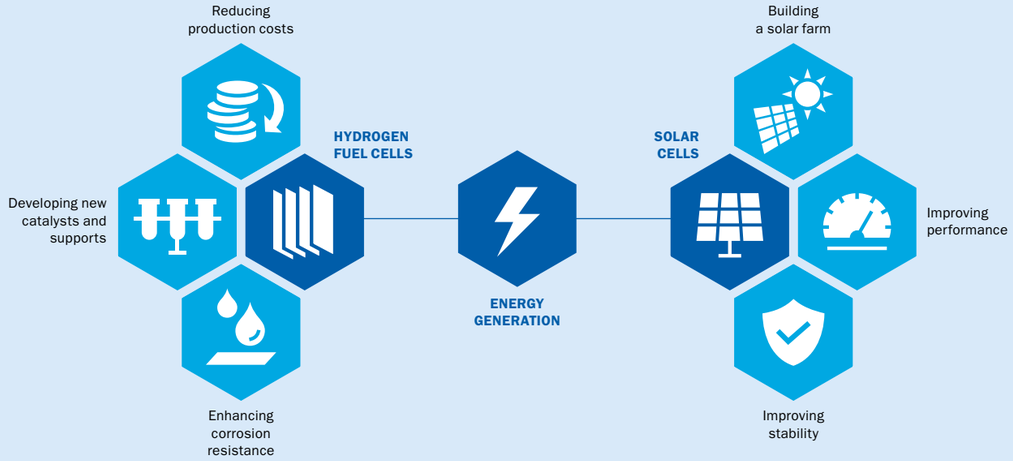
The main focus of our work on photovoltaics was to increase the manufacturing readiness level (MRL) of our devices. We achieved the first worldwide demonstration of nine

WORKING TOWARDS A SUSTAINABLE FUTURE

The levelised cost of energy for photovoltaics is already competitive with other energy sources, and technologies like our graphene-perovskite panels will help to reduce costs and improve performance and efficiency.

Our hydrogen fuel cells produce no greenhouse gases at the point of operation and are over twice as efficient than the target. Energy Generation directly contributes to SDG 7: for affordable and clean energy.

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



graphene-perovskite photovoltaic panels, which were integrated into a standalone solar farm system installed at Graphene Flagship partner Hellenic Mediterranean University, Greece. We are further assessing this technology in outdoor field tests.

We also developed two major approaches to fabricate graphene and layered material-based nanocomposites for fuel cells, and both are highly scalable and compatible with industry. One approach uses a high temperature pyrolytic method, producing nanocomposites that reduce the amount of platinum needed for a desired power output by over 50%. Our other approach is solution-based, requiring a lower temperature. The nanocomposites from this method were implemented in a small demonstrator and can operate without the need for complex support systems.

POWERED BY THE GRAPHENE FLAGSHIP

Thanks to the Graphene Flagship, we can collaborate with many other European institutions. This is extremely valuable: many of our academic partners have developed new supports and functional components, transferred to our industrial partners for upscaling, industrialisation and product launches. This cohesive ecosystem of research is highly effective.

For instance, collaborating with the Enabling Materials Work Package enabled us to synthesise graphene and layered materials with properties tailored to our applications, and our work with the Flexible Electronics Work Package helped us to develop our flexible, large-area electrodes. We also optimised our ink formulations in synergy with the Functional Foams and Coatings and Composites Work Packages, making them tunable for integration into photovoltaic devices.

These collaborations enable partners of the Graphene Flagship to share their characterisation facilities, like high-resolution transmission electron microscopy, which helped make our research more efficient. We also collaborate with various Spearhead Projects, such as GRAPES: a project to make cost-effective, stable graphene-enabled perovskite panels.

SAILING FORWARD

We aim to industrialise our photovoltaic devices for both on and off-grid applications. Our goal is to demonstrate commercial graphene-perovskite photovoltaic solar panels with large areas

Solar farm installation at HMU, Greece, allowing the benchmarking of graphene-perovskite panels for commercial technologies. Credit: HMU/Emmanuel Kymakis

of over 0.5 m^2 and high efficiencies above 14%. For fuel cells, we will continue to optimise their performance and durability, and aim to create large-area demonstrators large enough for automotive applications.

ON THE ROAD TO COMMERCIALISATION

The Graphene Flagship's upscaled production of graphene and layered materials propelled a number of our products forward, including our high-performing graphene-perovskite photovoltaic panels, their integration into working a solar farm, and our various functional components for fuel cell electrodes. These successes confirm the high TRL and MRL of our technologies.

Energy Storage

The Graphene Flagship has been, and continues to be, pivotal to our projects. It allows us to establish an effective value chain, from material production to industrial prototyping."

Vittorio Pellegrini
Work Package Leader

Work Package Leader
Vittorio Pellegrini, BeDimensional, Italy

Work Package Deputy
Daniel Carriazo, CIC Energigune, Spain

Improving electrochemical energy storage technologies with graphene and layered materials

In the Energy Storage Work Package, we investigate how integrating graphene and layered materials into electrochemical energy storage systems can improve their performance. How can we use graphene to develop safer batteries and supercapacitors that are more autonomous, with faster charge rates and longer lifetimes? This is the question that we seek to answer.

OUR STORY

Our Work Package was established in 2013 to investigate the energy storage and energy conversion applications of graphene and layered materials, with strongly research-oriented objectives. We then split into two different Work Packages to better focus our goals, with the Graphene Flagship scientists working on Energy Generation becoming a separate team. Over time, we introduced more and more companies to our project that are active in the production of graphene, and in the development of batteries and supercapacitors.

OUR RESEARCH

All applications of our research are closely related to improving electrochemical energy storage devices. In particular, we are developing lithium-ion, lithium-sulfur and lithium-metal batteries and supercapacitors, with improved performance to match the needs of our increasingly energy-hungry modern society – especially in the fields of transport and portable electronics.

HIGHLIGHTS FROM 2020

We developed three prototypes in 2020:

- Lithium-ion batteries with improved energy density. We achieved this by incorporating silicon-graphene composites into the battery's negative electrode
- Graphene-based lithium-ion capacitors. We made the electrodes by pyrolysing – thermally decomposing – coffee waste, with small amounts of graphene oxide. Our new electrodes improved the performance of these devices
- A highly stable lithium-sulfur coin cell, made from a self-standing, binder-free electrode, based on graphene with added sulfur.

We also developed an industrially compatible method to produce supercapacitor electrodes by spray-drying graphene-based suspensions.

POWERED BY THE GRAPHENE FLAGSHIP

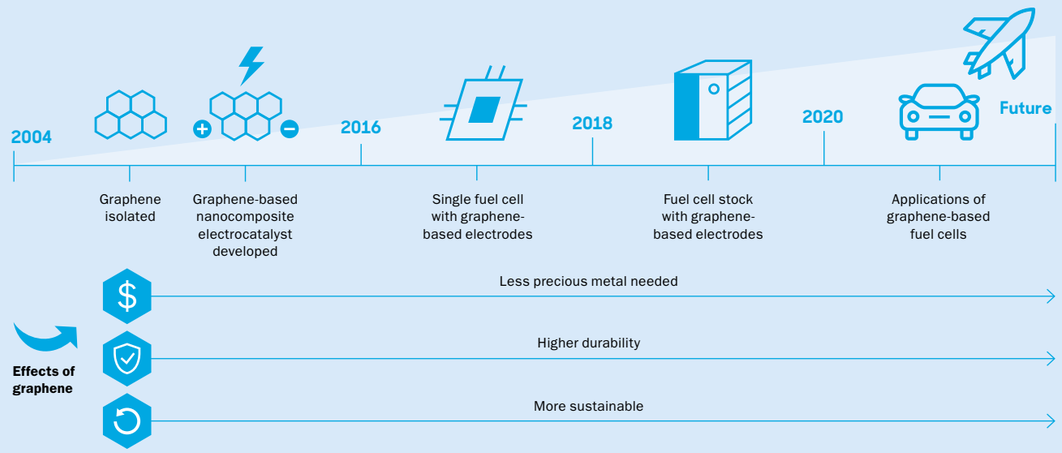
The Graphene Flagship has been, and continues to be, pivotal to our projects. It allows us to establish an effective value chain from material production to industrial prototyping, which is extremely valuable to the field.

WORKING TOWARDS A SUSTAINABLE FUTURE

By improving energy storage technology, we enable the development of a fossil fuel-free economy based on electricity. Batteries and supercapacitors are already the technology of choice for portable electronics, but key improvements are required if they are to make the leap to the transport sector and compete with internal combustion engines.

We need to improve their power and energy density efficiencies, lifetimes, recharging times and costs, together with endowing them with additional functionalities like flexibility. Most of these challenges require new materials for anodes and cathodes, graphene can be the key. This is the opportunity that our Work Package seeks to embrace.

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



SAILING FORWARD

We will continue our excellent fundamental research to gain insights into the impact of graphene on well-established technologies, such as lithium-ion batteries, as well as in next generation technologies, like metal-ion hybrid capacitors or lithium-sulfur and metal-air batteries.

At the same time, we will develop prototypes beyond conventional lithium-ion batteries, that incorporate graphene. For this purpose, we are collaborating with key European companies in the field – Graphene Flagship partners BeDimensional in Italy, NAWATechnologies and Thales in France, and Graphenea in Spain. We are also working closely with Graphene Flagship partnering research institutions, with a strong focus on technology transfer, to assist us with this process: CIC energiGUNE in Spain, imec in Belgium, IIT in Italy, and the University of Cambridge in the UK.

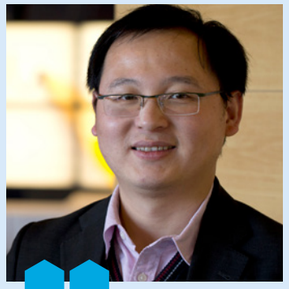
ON THE ROAD TO COMMERCIALISATION

We created demonstrators with technology readiness levels (TRLs) 3 and 4. Our lithium-sulfur batteries have a TRL of 3, our graphene-based spray gun-deposited electric double layer capacitors have a TRL of 4, and our silicon-graphene-based lithium-ion batteries have a TRL of 4. We aim for some of these technologies to reach TRLs of 5 to 6 in 2023.

The most advanced lithium-ion technology from our Work Package, based on silicon-graphene anodes, is being developed in the Batteries Spearhead Project.

Few-layer graphene powder produced in the BeDimensional pilot plant. Credit: BeDimensional

Functional Foams and Coatings



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

Work Package Deputy
Paolo Samorì, University of Strasbourg, France

The Graphene Flagship offers an unprecedented level of close collaboration between academic and industrial partners."

Xinliang Feng
Work Package Leader

Graphene-based foams and coatings for health monitoring, filtration and anti-corrosion applications

The Functional Foams and Coatings Work Package develops graphene-based foams and coatings for environmental applications, such as water and air purification, anti-corrosion coatings and health monitoring. Our principal goals are all closely aligned with the European Union's environmental protection policies, such as the Paris Agreement and the UN's Sustainable Development Goals.

OUR STORY

During the first Core phase of the Graphene Flagship, our activities focused on functionalising graphene and layered materials, and processing them into foams, membranes and coatings for applications in electronics, energy and environmental protection. These developments corresponded to a technology readiness level (TRL) of 3.

In the second Core phase, we validated our water and air filtering membranes, pressure sensors and anticorrosion coatings, and pushed them towards industrialisation and commercialisation with a TRL of 5. Now, in the current Core phase, two of these technologies have been adopted by leading European companies to form two all-new industry-led Spearhead Projects: AEROGrAFT and GRAPHIL.

In the AEROGrAFT project, Graphene Flagship partner Lufthansa Technik will develop a new, highly efficient air filtration for their aircraft using the air purification technology produced by our Work Package. The GRAPHIL project seeks to develop portable water purification devices using our membrane filtration technology, in collaboration with Graphene Flagship partner Medica SpA.

OUR RESEARCH

Together with Graphene Flagship partner Barpimo, Spain, we are developing environmentally friendly waterborne and graphene-based anticorrosion paints for the automotive industries. We are also developing pressure sensors, in collaboration with Graphene Flagship partner STMicroelectronics, Italy, to monitor the health of drivers. This technology uses graphene-based pressure sensors to monitor drivers' heartbeats and provide a 3D pressure map to keep track of their vital signs.

In addition, together with Graphene Flagship partners Sixonia Tech and Phi-Stone, Germany, we are developing self-cleaning graphene-based filter masks to protect against viruses and bacteria. The highly porous graphene materials in the masks can be heated up to 400 °C in just a few milliseconds, requiring low amounts of energy, which rapidly destroys bacteria and viruses.

HIGHLIGHTS FROM 2020

We developed capacitive desalination technology for water purification, based on graphene and layered materials, capable of removing more than 60% of the salt from seawater. The technology consumes 90% less energy than reverse osmosis, the current standard method.

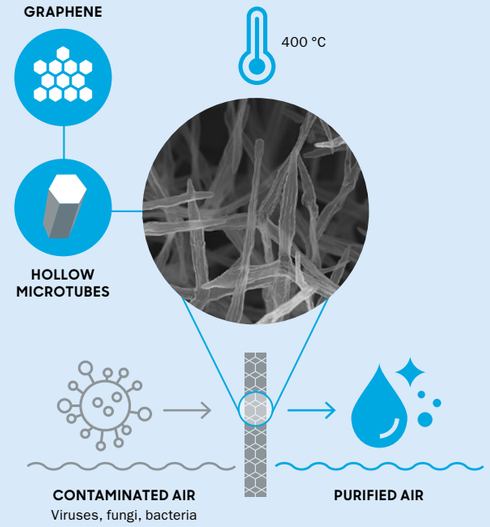
In addition, we produced a highly efficient graphene and layered material-based technology for air and water filtration, and launched two Spearhead Projects for the current phase of the Graphene Flagship, AEROGrAFT and GRAPHIL, in collaboration with industry leaders Lufthansa Technik and Medica.

WORKING TOWARDS A SUSTAINABLE FUTURE

Sustainable development is the main focus of the Work Package. Our air and water purification technologies have high societal impacts, and they could address the growing worldwide demand for a cleaner environment.

Together with these technologies, our health monitoring sensors could also increase quality of life and reduce the number of preventable deaths by keeping track of patients' vital signs.

New generation of active filter materials for health protection and fight against pandemics



- STERILISES PATHOGENS
- SELF-CLEANING
- REUSABLE
- SMART FILTRATION

ON THE ROAD TO COMMERCIALISATION

Several industrial partners of this Work Package, like Sixonia Tech, have already taken various products to the market, such as graphene and layered material-based inks and formulations.

Our Work Package will continue to further develop our products to TRLs 6 to 7, and introduce them to European companies to begin the process of commercialisation. This strategy was successful in the previous phase of the Graphene Flagship, when Medica and Lufthansa Technik joined the project.

On top of this, pressure sensors developed by our partners are now being tested in hospitals by healthcare professionals.

POWERED BY THE GRAPHENE FLAGSHIP

The large-scale, long-term funding provided by the Graphene Flagship has been essential. Some areas of research require more time and more secure funding to fully flesh out their ideas and successfully transfer knowledge from the lab to an industrial or commercial environment. In this way, the Graphene Flagship has been invaluable.

Furthermore, the Graphene Flagship offers an unprecedented level of close collaboration between academic and industrial partners. Instilling trust between these two key research sectors is crucial.

SAILING FORWARD

In the previous phase of the Graphene Flagship, 18% of our Work Package was made up of industrial partners. In the current phase, that percentage has increased significantly to 40%. This highlights the motivations and effectiveness of our Work Package's efforts to industrialise and commercialise our new technologies.

Going forward, we will continue to develop technologies based on graphene and layered materials for desalination, anti-corrosion coatings and monitoring sensors for environmental factors. We will also extend our activities to cover other areas of environmental concern, such as antibacterial or antiviral coatings for surfaces, and antibacterial or antiviral air conditioners and filters.

Composites

Work Package Leader
Costas Galiotis, FORTH, Greece

Work Package Deputy
Ian Kinloch, The University of Manchester, UK

We are pursuing the applications of graphene and layered materials for all main types of composite: thermoplastics, thermosets, elastomers and inorganic composites."

Costas Galiotis
Work Package Leader

Making composites based on graphene and layered materials to meet the needs of industry

The Composites Work Package develops high-performance composites based on graphene and layered materials. These meet the requirements of a broad range of industrial sectors, from the aerospace and automotive industries to energy generation and storage. Graphene composites are poised for rapid implementation and large-scale production, which is reflected by our Technology and Innovation Roadmap.

We are pursuing the applications of graphene and layered materials for all main types of composite: thermoplastics, thermosets, elastomers and inorganic composites.

OUR STORY

Our Work Package launched in 2013 during the 'ramp-up' phase of the Graphene Flagship. At the time, we mostly focused on fundamental research to improve the integration of graphene and layered materials into composites, studied processing methods, and assessed their performance. We were very successful: by 2016, we had taken several composites into the market.

This momentum continued into Core 1, the beginning phase of the Graphene Flagship, with our developments focused on new graphene composite formulations. These brought enhanced multifunctionality and promising commercial applications when integrated in real devices. By the end of Core 2 we had developed several products, prototypes, patents and new technologies.

Now that we have sailed into Core 3, our main goal is to capitalise on the knowledge and experience we have gained thus far, and focus on increasing the technology readiness level (TRL) of our systems, expanding the value chain into a variety of key industrial sectors in Europe.

OUR RESEARCH

The work conducted by the Composites Work Package has applications across various different industries, including aerospace, automotive, electronics and construction. This is mainly due to the Graphene Flagship's value chain strategy, which enables and promotes collaboration between academic and industrial partners. Here are just a few of the applications of our research:

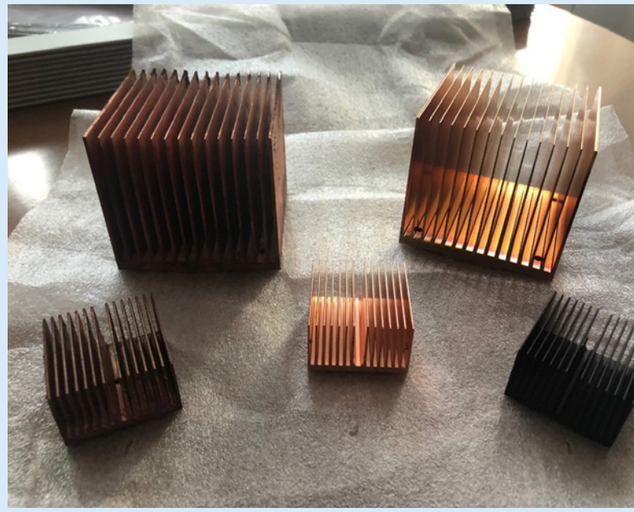
- We developed production methods for graphene and layered material masterbatches, enabling their diffusion into the plastics industry, where the materials' properties are tailored to the needs of the end-users
- Our efforts to integrate graphene and layered materials into fibre-reinforced plastics led to lighter materials with improved performance, reducing assembly and maintenance costs, as well as fuel consumption and carbon emissions

WORKING TOWARDS A SUSTAINABLE FUTURE

Graphene and layered materials can make composites stronger and more durable. This could lead to longer-lasting products that cost less to maintain. Coatings like Graphene Flagship Associated Member Talga's graphene-based Talcoat product can significantly improve a material's durability. Thanks to graphene, Talcoat protects marine vessels from corrosion.

Composites based on graphene and layered materials can improve batteries and electronic devices, saving energy and reducing waste. Furthermore, introducing graphene and layered materials to recyclable thermoplastics or fibre composites can reduce their costs to manufacture and generate less waste.

Graphene Flagship researchers performing the spectroscopic characterisation of graphene-based nanolaminates. Credit: Nanesa



Graphene-based radiators coated through an electroplating process. Credit: FORTH

- We incorporated graphene and layered materials into elastomers to further improve their properties, making them more flexible with better mechanical properties, low shrinkage, high chemical resistance and high thermal stability
- Graphene and layered materials containing inorganic components, like metallic powders, nanoparticles or nanofibers, improved the thermal and electrical efficiency of conductors, reduced friction and wear, and enhanced the environmental protection capabilities of coatings.

HIGHLIGHTS FROM 2020

We made progress in several key areas. We submitted several new patents, fabricated new thermoplastic composites based on graphene and layered materials with improved dispersion, developed new prepregs – composite materials made from 'pre-impregnated' fibres – and more. We also launched a value chain for the automotive industry.

POWERED BY THE GRAPHENE FLAGSHIP

We recognise the value of collaboration enabled by the Graphene Flagship. On top of bringing researchers together from across Europe, to foster new collaborations and nourish existing ones, the Graphene Flagship enables easy and efficient knowledge transfer, supporting new pursuits and developments. The Composites Work Package actively promotes collaboration between the other Graphene Flagship Work Packages, as well as our Associated Members and Partnering Projects, both through individual interactions and larger gatherings at workshops and events.

Our research led to the creation of several Graphene Flagship Spearhead Projects. For instance, the graphene heating system for ice protection, developed in the Composites Work Package, is used by Airbus-led project GICE to enhance the TRL of their anti-icing systems in accordance with the needs of the aeronautics industry. We developed a mixed metal and graphene material for self-lubricating contacts, exploited by the Circuitbreakers Spearhead Project, led by ABB, to design high-TRL applications for the energy sector.

ON THE ROAD TO COMMERCIALISATION

The Composites Work Package has progressed towards high TRLs. In Core 2 we developed 10 products and 38 prototypes, and submitted 10 patent applications.

There are already a number of Graphene Flagship products on the market, from graphene powders and inks to thermal coatings and sports helmets. The new generation of graphene and layered material masterbatches have TRLs between 3 and 7, and the new thermal management systems have TRLs between 4 and 7. Both of these applications will evolve into commercial products soon.

SAILING FORWARD

Our main objective is to maximise the Graphene Flagship's innovation output by targeting the key successes from previous phases, and developing new composite technologies using graphene and layered materials.

We will optimise our most promising applications to produce new prototypes and products with high TRLs for the automotive, aerospace, construction and power transmission industries. We will continue to enhance the value chains established for the automotive and aerospace industries.

GRAPHENE FLAGSHIP ANNUAL REPORT 2020

Production

Work Package Leader
Alex Jouvray, Aixtron, UK

Work Package Deputy
Julio Gómez-Cordón, Avanzare, Spain

One of the most critical duties of our Work Package is to provide materials for all partners of the Graphene Flagship.”

Alex Jouvray
Work Package Leader

Producing high-quality graphene for other Work Packages and partners

The Production Work Package develops a wide range of commercial products, taking advantage of the leadership and experience of our members, all of whom are industrial partners. We use graphene to improve the performance of our commercial products, and we produce and distribute commercial quality graphene to the other Graphene Flagship partners.

OUR STORY

The ethos of the Production Work Package has remained the same from the very beginning of the Graphene Flagship. We seek to answer the following question: “How do you take new products and materials all the way to an industrial setting?”

Our strategy is to focus on the needs of our industrial partners, who develop new applications of graphene and layered materials to meet market demands. One of our most critical duties is to provide materials for all partners of the Graphene Flagship. These materials have a known, defined quality, and they are manufactured and measured in accordance with accepted quality standards.

OUR RESEARCH

Our industry-led products in development include LED devices to disinfect water, air and surfaces, chemical vapour deposition (CVD) graphene coatings to improve the durability of copper wires, and in-line monitoring technologies for graphene production. We are also working on graphene coatings for dry lubrication, and new materials based on graphene and layered materials for applications in aerospace. We are developing multifunctional graphene and layered materials for applications in corrosion and fire protection.

HIGHLIGHTS FROM 2020

We made a number of significant achievements:

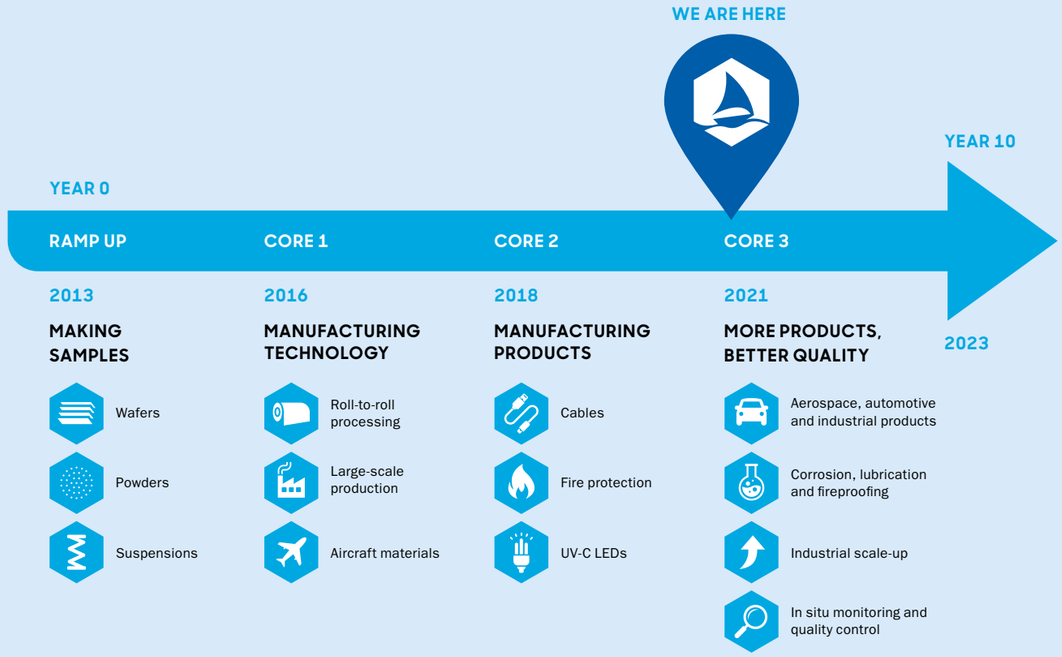
- We developed a graphene-based UV-C LED to disinfect surfaces, water and air
- We produced full-scale sections of an Airbus A350 wing, and tested them under real conditions. Our tests showed that graphene and layered materials significantly improve the material strength, without negatively impacting the mechanical properties
- We used high-quality CVD graphene to improve the conductivity of copper wires by more than 1%, stable in a normal environment for over 18 months
- We tested our flame-retardant materials for building and automotive applications in accordance with industrially relevant standards. The tests showed that graphene and layered materials significantly improve the ability to protect against fire.

WORKING TOWARDS A SUSTAINABLE FUTURE

The majority of our work addresses sustainable development. For example, our UV-C LED purification technology could replace other methods, like mercury lamps, which are very inefficient and require hazardous components.

Our work on graphene and layered materials for aerospace applications could reduce the overall mass of planes, hence lowering their environmental impact. Our work on wires and coatings could enhance their conductivity, therefore reducing their mass and production cost, and improve their shelf-life, which reduces waste.

Graphene and layered materials could also replace traditional materials for corrosion and fire protection. This will lead to safer, more durable buildings and vehicles.



POWERED BY THE GRAPHENE FLAGSHIP

Thanks to the Graphene Flagship, the producers of graphene for our Work Package can interact with all members of our European consortium, including partners in academia and industry, Associated Members and partnering projects. This is hugely beneficial for researchers developing graphene-containing products, as we can provide them with the right sorts of graphene and layered materials they need for their specific applications.

SAILING FORWARD

Our key products are being developed and matured to higher technology readiness levels (TRLs).

We are developing a new in-line metrology tool measure graphene’s key parameters during its production and growth. We are also expanding our work on graphene coatings for wires, from just CVD graphene on copper, to other types of graphene and layered material on a wider range of wires.

Our work on fire protection is highly promising, and fire sensors based on graphene and layered materials are also being developed to include larger products, like pipes and tanks.

Furthermore, our work on aerospace materials will see the addition of new manufacturing processes, to make a variety of components for the Airbus A350 airplane. Graphene enables lighter materials for aviation, consequently reducing fuel consumption and emissions, in line with Europe’s sustainability agenda for a climate-neutral economy.

ON THE ROAD TO COMMERCIALISATION

A wide range of products developed in our Work Package are already on the market, such as Aixtron’s NEUTRON system for continuous graphene production, Grupo Antolin’s graphene-based King Cobra tennis racket, and Avanzare’s paints and coatings for industrial applications.

Most partners of the Production Work Package aim to release at least one commercial product before the end of 2023.

GRAPHENE FLAGSHIP ANNUAL REPORT 2020

MEET THE PARTNERING DIVISION

Fostering collaboration with our Associated Members and Partnering Projects

The Graphene Flagship has catalysed research and innovation in the realm of graphene and layered materials since the very beginning. Covering both fundamental and applied science, the consortium nourishes a diverse and multidisciplinary environment with more than 250 organisations all over Europe. Among them are the Graphene Flagship's 107 Associated Members and 37 Partnering Projects, all participating in the Partnering Division. These represent one of the most fruitful endeavours of the Graphene Flagship, and expand our collaborative ecosystem by building a wider network of research facilities and experts.

Our Associated Members are a cohort of academic institutions, SMEs and industrial collaborators affiliated with the Graphene Flagship, all with tremendous potential for innovation in the field of graphene and layered materials. Furthermore, our partnering projects, are initiatives funded by the European Union and Member States – often through the FLAG-ERA consortium – that team up with the Graphene Flagship, enabling cross-collaboration and promoting original discoveries.

"The Partnership Division plays an ever-increasing role in the evolution of the Graphene Flagship, from fundamental research to innovation, with unprecedented potential. It facilitates the building of a European network of facilities and experts in the field of graphene and layered materials," explains Partnering Division Leader Yuri Svirko, from Graphene Flagship Associated Member the University of Eastern Finland.

In this article, learn about the science behind a handful of our partnering projects and Associated Members, all belonging to the Graphene Flagship's Partnering Division.

Haydale

ASSOCIATED MEMBER
A new and improved way to make graphene oxide

Using its patented plasma process, Haydale Graphene Industries produced graphene oxide with a functionalisation level of 28% atomic percent oxygen: comparable to wet chemical methods and suitable for the existing graphene oxide market.

Making graphene oxide using wet chemistry methods is labour and time-intensive, and involves environmentally hazardous by-products and unstable intermediates. To the contrary, Haydale's process needs no solvents or harsh chemical treatments. Moreover, their technology is scalable, single-stage, dry and environmentally friendly. Their new system also applies to hydrophilic, hydrophobic, carboxylic, amine and oxidative modifications with the same environmentally friendly and scalable process.

ETMOS

PARTNERING PROJECT
Integrating graphene and layered materials into insulators for semiconductor manufacturing

Insulating materials with high dielectric constants are in demand for semiconductor manufacturing processes. Integrating graphene and layered materials like transition metal dichalcogenides (TMDs) is important for several next-generation electronics and sensing devices.

Funded by FLAG-ERA, ETMOS is a Graphene Flagship partnering project with a mission to deposit epitaxial graphene and TMDs onto wide-bandgap hexagonal semiconductors. To do this, they used a method called atomic layer deposition, adding aluminium oxide layer-by-layer on top of epitaxial graphene. This is one of the best methods to obtain high-quality, ultra-thin insulators that are uniform over a large area.
The team successfully obtained uniform and ultra-thin aluminium oxide films atop epitaxial graphene with no pre-functionalisation. They expect this will lead to new graphene-based applications in electronic devices and sensors.

Graphensic

ASSOCIATED MEMBER
A graphene-based magnetic field sensor for advanced position detection

Graphensic created a graphene Hall sensor using epitaxial graphene to detect magnetic fields, outputting an analogue signal proportional to the intensity of the field. Their device will be useful for various applications that require high performance position detection, like autonomous driving.

Their sensors are 10 times more sensitive to magnetic fields than conventional silicon-based Hall sensors. They also detect magnetic fields with record-low detection limits compared to semiconductors, and all other graphene-based Hall magnetic field sensors, up to 150 °C. Using epitaxial graphene makes the production process scalable, and the results show that Hall sensors based on epitaxial graphene outperform existing Hall sensors between -55 °C and 125 °C.

CERANEA

PARTNERING PROJECT
Making graphene-filled ceramic sandwiches by hot-pressing

Researchers working on the FLAG-ERA-funded CERANEA partnering project are developing graphene multilayer ceramic sandwich composites, a type of ceramic material filled with graphene, using a process called hot isostatic pressing. The structure features two alternating layers, like a sandwich: one layer contains porous silicon nitride and 30% graphene by weight, while the other contains densified silicon nitride and only 5% graphene by weight. Incorporating graphene into ceramic structures in this way increases their durability and conductivity.

The team also studied ceramics based on silicon nitride and zirconia with varying amounts of multi-layered graphene. Through their studies, they identified the optimal graphene, silicon nitride and zirconia 'sandwich' – a layer of 30% multilayer graphene (MLG) by weight sandwiched between two layers of just 5% MLG. This configuration resulted in a two-to-three-fold improvement in the mechanical properties, compared to the opposite ratio.

GATES

PARTNERING PROJECT
Graphene-based membranes for filtration, sensing and more

The GATES partnering project, also funded by FLAG-ERA, developed a new graphene-based membrane for gas filtration, sensing devices and microelectromechanical systems. Their filter is based on graphene made by chemical vapour deposition, suspended above holes in a silicon substrate, and now they have applied to patent their technology.

Using their method, the GATES scientists can effectively fabricate large areas of their membrane. It is also compatible with batch fabrication, meaning they can make several devices in parallel at the wafer scale using technologies compatible with the semiconductor industry.

SOgraphMEM

PARTNERING PROJECT
A step towards graphene spintronics

Graphene-enabled spin logic devices could surpass Moore's law predictions and shape the future of computing, thanks to their enhanced ability to store information. Researchers working on the FLAG-ERA-funded SOgraphMEM project demonstrated that graphene, coupled with ferromagnets and heavy metals, meets all the requirements to create spin textures. These are interesting patterns of spin polarisation that could be used as building blocks for future memory devices with long spin lifetime and propagation, even at room temperature. In particular, they modelled the formation of stable magnetic skyrmions, a hot topic in spintronics for its potential use in next-generation memory and logic devices, with a thin sheet of a ferromagnetic metal – cobalt – sandwiched between layers of heavy metal and graphene.

The team also explained how cobalt atoms penetrate through the graphene sheet to form a layer on two different heavy metal surfaces. The mechanism enables the growth of high-quality, flat cobalt layers with tailored magnetic properties. This results in a trilayered structure that allows graphene's structural and electronic properties to be tuned for the development of graphene spintronics.

Innovation

The goal of the Innovation Work Package is to create stronger links between Graphene Flagship research and external market opportunities.”

Kari Hjelt
Work Package Leader

Work Package Leader
Kari Hjelt, Chalmers Industriteknik, Sweden

Work Package Deputy
Francesco Bonaccorso, BeDimensional, Italy

Charting the course towards higher technology levels

The overall goal of the Innovation Work Package is to maximise the innovation potential of the Graphene Flagship’s most valuable research. This is done through the creation of new ventures, commercialising products and services through partnerships, and by licensing intellectual property rights. We have a strong focus on business development and support for knowledge management and intellectual property.

OUR STORY

The need for an Innovation Work Package in this kind of project was not self-evident at the beginning. However, the growing complexity of the Graphene Flagship suggested that a systematic way to form and handle innovation policy and actions was needed. Our Work Package has since grown substantially, consistently towards a more hands-on approach focused on organising industry events and growing our network of Business Developers.

HIGHLIGHTS FROM 2020

Our business development activities yielded great results over the past year. The Business Developers were instrumental in the launch of spin-off company INBRAIN Neuroelectronics. In June, INBRAIN received a €1 million investment from Sabadell Asabys, Alta Life Sciences, ICF and Finaves, and in November, they received an additional award of €100,000 from BStartup Health – Banco Sabadell’s program dedicated to supporting innovative health projects. Read more about this and other Graphene Flagship spin-offs on **page 58**. Graphene Flagship Business Developers also supported the creation of the current Spearhead Projects, and work to promote their commercialisation goals. Read more about the Spearheads on **pages 8 to 19**.

For electronics applications, our Business Developers helped to connect graphene supplier Graphenea with institutional partner Fraunhofer IZM to develop a graphene sensor for COVID-19 antibody tests, using a platform that can detect the disease from a single drop of blood or saliva within 15 minutes. The technology is expected to ramp up to high-volume production.

The launch of the Graphene Flagship’s Experimental Pilot Line is expected to impact many applications for graphene and layered materials, and the Business Developers provide support for the project – both by developing a business plan for the initiative and by helping to connect the project to key players in their industries. In terms of optoelectronics and photonics, the launch of a manufacturing facility for graphene-based optoelectronics products is a valuable bridge to encourage the commercialisation of graphene-based proof-of-concepts or prototypes.

The Innovation Work Package also organised an Innovation Workshop for Electronics, together with RISE and SIO Grafen, on the 12 November 2020. These workshops aim to foster collaborative innovation projects within and outside of the Graphene Flagship consortium. The workshop was by invitation only and hosted 87 participants from 15 countries: 21 from research institutes, 25 from universities, seven from consulting firms and 28 from small and medium enterprises.

In addition, the Innovation Education and Training Platform is open to the public, and offers a host of video courses and resources covering a range of topics, including intellectual property, patenting, start-up creation, technology transfer, venture capital and more, with an emphasis on hands-on techniques, as well as subjects of specific relevance to the Graphene Flagship and the graphene market.

WORKING TOWARDS A SUSTAINABLE FUTURE

We work towards to Europe’s overall sustainability strategy in several ways. Innovation offers business development support that helps other Work Packages and Spearhead Projects promote their activities and reach their goals. This increases the Graphene Flagship’s innovation output in terms of intellectual property, new ventures, commercialised products and services and licensed technologies.

Narrow columns: number of priority patent applications (new inventions) filed in each of the main Graphene Flagship reporting periods.

Wide columns: total number of patent applications (including priority applications) with a priority date in each of those reporting periods.

Circles: number of granted patents in each reporting period, by the reporting period of each patent application’s respective priority date. For example, 13 of the patent applications having a priority date between October 2013 and March 2016 matured into granted patents between April and December 2020. Credit: Credit: Eric Ramberg/CIT

Innovation also played a visible and important role in the digital events that took place in 2020, including some key Graphene Flagship events like the Graphene for Research, Innovation and Collaboration event in September, which featured an entire day dedicated to innovation and industrialisation efforts within the Graphene Flagship.

SAILING FORWARD

The Work Package’s overall goals remain the same, but moving forward we will focus on concrete actions. In particular we will work to raise the technology readiness levels of Graphene Flagship outputs and support the Spearhead Projects and the Experimental Pilot Line. The goal is to create stronger links between Graphene Flagship research and external market opportunities.

ON THE ROAD TO COMMERCIALISATION

It takes years for a patent application to mature into a granted patent, and many patent applications are abandoned, are withdrawn, or expire. As a ten-year project, the Graphene Flagship tracks patenting metrics over a longer time than is typical, from the first-filed patent application describing an invention (the so-called “priority application”) through to the subsequent “family” of related patent applications that “claim priority” to the priority application. A typical family comprises two to five patent applications that share a priority date fixed by their respective priority application. The evolution of each patent application (to abandonment/withdrawal or a granted patent) is tracked by country and technologies.

Dissemination

Work Package Leader
Rebecca Waters, Chalmers University of Technology, Sweden

Work Package Deputy
Fernando Gomollón-Bel, The University of Cambridge, UK

Our team of experts ensures that the project's success is visible to all of our stakeholders."

Rebecca Waters
Work Package Leader

Spreading the word about graphene research and innovation

The Dissemination Work Package magnifies the impact of the Graphene Flagship's contribution to European research and innovation by sharing information through our website, events, media outreach, participation in tradeshows and exhibitions and social media channels. Our team of experts ensures that the project's success is visible to all our stakeholders.

OUR STORY

Like the Graphene Flagship, the Dissemination team started out small, focusing largely on fundamental science. Over the years, we have grown and evolved along with the project. Our team has expanded its personnel and its expertise to match the needs of an increasingly industry-facing initiative.

NEW BRAND IDENTITY

With the launch of the Graphene Flagship's Core 3 phase in April 2020, Dissemination shifted its messaging and brand image to be clearer, more polished and more focused on high-technology readiness level (TRL) commercial output. This approach helps to put the Graphene Flagship in a better position at industrial trade shows, in business development activities and through new commercial ventures that are essential to meeting the project's goal of bringing graphene out of the lab and onto the market.

To this end, our Work Package has refreshed the Graphene Flagship's logo and brand identity to give it a cleaner, more dynamic look and message. Our new logotype is more than just a small rebranding. Take a closer look – our flagship now has more wind in its sails, pushing it to the forefront of European innovation. The waves are bigger, but the ship is sailing boldly and confidently into a successful future. The Graphene Flagship's new brand guide gives a clearer message about the project and its objectives and gives guidance to ensure that our look, tone and style are consistent in all of our communications. A new PowerPoint template, updated marketing materials and a redesigned Annual Report and Graphene Magazine allowed the Graphene Flagship to make a bigger splash in 2020.

This all comes with a broader brand refresh that will help us to better depict the multidisciplinary activities of the Graphene Flagship. Our social media channels had a variety of different usernames, which made it hard to find us. Now, we have unified our identity across all platforms: we are **GrapheneEU**. It is clearer and, like our newly refreshed brand, more inclusive of the different initiatives carried out within the Graphene Flagship framework.

NEW WEBSITE

The last piece of the rebranding puzzle was the new and improved Graphene Flagship website launched in December. The new site looks more modern, professional and visually pleasing, with more integrated graphics and videos.

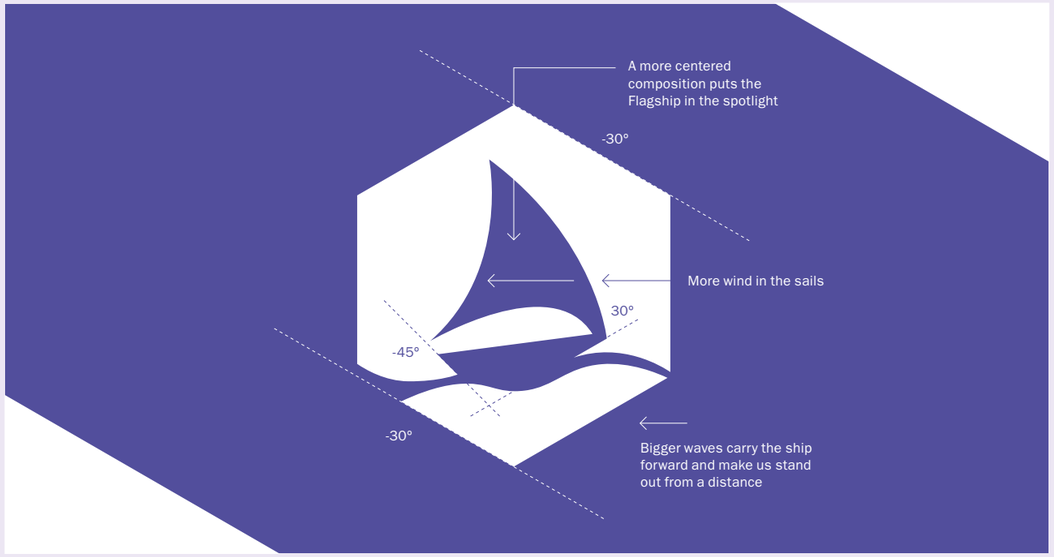
Moreover, the redesigned navigation makes it easier for outside parties to learn about the Graphene Flagship, stripping out much of the project's internal jargon and putting the most relevant information in more visible positions. New sections highlighting spin-off companies, the Technology and Innovation Roadmap and the Experimental Pilot Line showcase the Graphene Flagship's progress toward its commercialisation goals.

HIGHLIGHTS FROM 2020

The past year has presented some unique challenges for Dissemination. With all physical events cancelled from March, our events and marketing team had to reinvent their activities. We launched the Graphene Hub, a portfolio of digital events including several events covering specific graphene areas – Energy Storage and Healthcare – as well as a broader event covering the full range of Graphene Flagship topics: *Graphene for Research, Innovation and Collaboration*. These events were presented on a variety of platforms depending on the audience and the degree of attendee interaction needed. *Graphene for*

WORKING TOWARDS A SUSTAINABLE FUTURE

Dissemination has been actively working on greener marketing and events. We use sustainable paper for marketing materials, like this Annual Report, and the gifts we give away at events are manufactured from sustainable materials. Digital events have also limited the need for travel within the consortium, reducing our carbon footprint and broadening our reach.



The new Graphene Flagship logo puts wind in our sails, and makes us more recognisable from a distance. Credit: Dahlbäck/Söderberg

Research, Innovation and Collaboration, for example, included speed networking sessions as well as the opportunity for one-on-one networking and meetings.

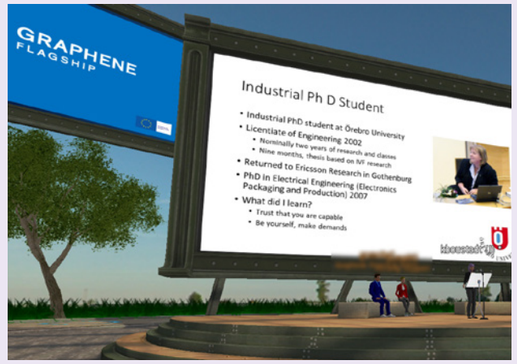
Perhaps the most innovative digital event held in 2020 was the *Women in Graphene* Career Day, which was held in a virtual world where participants attended as avatars. Delegates could walk to the Graphene Flagship booth, enter the auditorium for the presentations, sit in a networking lounge and participate in group discussions.

With the launch of the current phase of the project, the *Women in Graphene* initiative evolved into *Diversity in Graphene*. This expands the previous task to provide support for all under-represented groups in the Graphene Flagship community and promote inclusion throughout the project. This task was moved from the Management Work Package to Dissemination. *Diversity in Graphene* also now includes a mentoring programme which kicked off last fall. Over 30 participants were paired off and offered training on effective mentoring to ensure that both mentors and mentees understood the process and their role in a successful mentorship programme. The pairs will meet monthly over the next year.

SAILING FORWARD

Over the next few years, Dissemination will continue to focus its efforts to highlight high-TRL Graphene Flagship outputs, forwarding the project's goals to commercialise graphene for the benefit of the European economy and society. This will be possible with the increased visibility of products and industrial outputs on the Graphene Flagship website, as well as through a new series of product videos that will be produced over the next year.

/GrapheneEU



The *Women in Graphene* Career Day immersed participants in a virtual world that allowed attendees to join sessions in the auditorium, network in groups or one-on-one and participate in hands-on skills training. Credit: Graphene Flagship

Management

The Graphene Flagship's strength is in bringing together key European players from research and industry."

Jari Kinaret
Graphene Flagship Director

Work Package Leader
Jari Kinaret, Graphene Flagship Director

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

Keeping the Graphene Flagship on course through effective coordination

The Management Work Package ensures that the Graphene Flagship operates as it should, by facilitating regular project reports, compiling information about the project's progress, organising governing body meetings, liaising with the European Commission and collaborating with the Partnering Division and the Innovation, Dissemination and Industrialisation Work Packages.

OUR STORY

From the start of the project, our Work Package has been a cornerstone to keep the project running smoothly and ensure that the project's outputs are properly monitored and reported on. In addition, we were instrumental in the growth of the project, facilitating the expressions of interest that bring new competencies to the Graphene Flagship, and coordinating the addition of new initiatives like the Spearhead Projects.

HIGHLIGHTS FROM 2020

The past year was particularly momentous. In April, Management brought the Graphene Flagship's Core 2 phase to a successful close, and launched Core 3, the current phase of the Graphene Flagship Core project. This involved additional coordination, as the final evaluation had to be conducted electronically, rather than in person. The Management Work Package also created a prototype brochure and a series of product and prototype videos to replace the physical demonstration session, typically held in person during the European Commission's review, effectively showcasing the Graphene Flagship's results. Closing one Core project and launching another comes with a great many challenges, and Management seamlessly solves them behind the curtains.

The coronavirus pandemic had impacts beyond switching to a digital evaluation of Core 2. In 2020, our Work Package worked to secure a six-month extension for the Graphene Flagship Core project to compensate for the months of lost laboratory time when researchers were unable to access their workplace or their results. While the Graphene Flagship will not be granted additional money for the extension, partners will have additional time to meet their goals and to use the funding allocated to them.

The lockdown halted all in-person events, which put a hold on the International Workshops that Management typically coordinates through the European Science Foundation (ESF). These workshops facilitate collaboration between European researchers and those in other countries or regions. The Graphene Flagship also had to cancel its Annual Meeting and host the General Assembly digitally.

POWERED BY THE GRAPHENE FLAGSHIP

The Graphene Flagship's strength is in bringing together European players from research and industry to collaborate on solutions that would be impossible for the individual parties to accomplish. The project helps technologies overcome the so called 'valley of death' from research to industrial application.

Management facilitates and broadens these collaborations through the partnering mechanism managed by the ESF. By welcoming Associated Members and Partnering Projects into the Graphene Flagship ecosystem, the project is able to broaden its experience base, reach and impact. Through its management of the partnering mechanism, the ESF helped to significantly increase the number of Associated Members and Partnering Projects from one phase of the project to the next. Furthermore, its management of FLAG-ERA calls helps to bring in additional expertise and funding to the project.

Jari Kinaret, Graphene Flagship Director, explains the advantages of graphene for VARTA Micro Innovation's new coin cell batteries to European Commission Executive Vice President Margrethe Vestager. Credit: Rebecca Waters

ON THE ROAD TO COMMERCIALISATION

Vice President Vestager appreciated the collaborative ecosystem established by the Graphene Flagship, which has enabled the creation of new spin-off companies, innovative devices and patents – nourishing the growth of a wealth of vital scientific knowledge, and making a real impact on the European economy.

A VISIT FROM VICE PRESIDENT VESTAGER

Before coronavirus restrictions were put in place, Management and Dissemination collaborated to host European Commission Executive Vice President Margrethe Vestager at the Graphene Flagship headquarters at Chalmers University of Technology, Sweden. Vice President Vestager handled and tested the newest Graphene Flagship products, prototypes and demos from various industrial sectors, from graphene-enabled wearables and sensors to high-capacity batteries and airplane parts.

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

Credit: Stine Heilmann

It is incredible to see how well the project is administered. The Graphene Flagship is money well spent!"

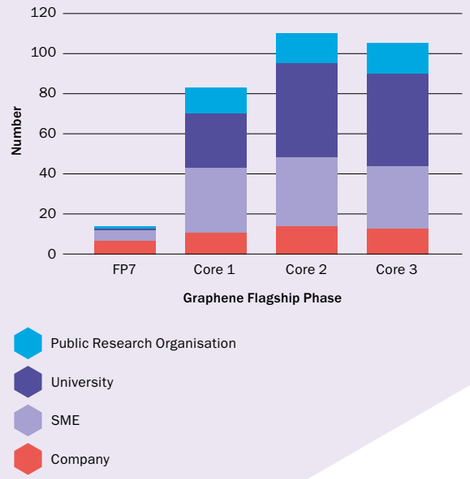
Margrethe Vestager
European Commission
Executive Vice President

SAILING FORWARD

With the launch of the Experimental Pilot Line (2D-EPL), our Work Package helped the Graphene Flagship to make a significant mark on its course towards industry adoption of graphene and layered materials. Read more on **page 46**. Over the past year, Management worked to modify the structure of the Graphene Flagship contract to allow for a second project, the 2D-EPL, which was launched in October 2020 with a €20 million budget for four years.

Partnering Division members associated to the Graphene Flagship

The ESF has helped to expand the Graphene Flagship's collaborations and knowledge base through its support for Associated Members and Partnering Projects.



Industrialisation

Work Package Leader
Alexander Tzalenchuk, National Physical Laboratory, UK

Work Package Deputy
Thomas Reiss, Fraunhofer ISI, Germany

The Graphene Flagship community is an indispensable pool of expertise in everything we do.”

Alexander Tzalenchuk
Work Package Leader

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 into 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 the properties and characterisation of graphene and layered materials, as well as devices, components and systems enhanced by them
- Communicating characteristics and specifications transparently via the Samples and Materials Database.

OUR STORY

The Work Package’s industrialisation agenda has evolved as the technology based on graphene and layered materials has matured, and as the industry that uses them has emerged. Initially in the Core 1 phase of the Graphene Flagship, we focused on forecasting the general trajectory of the technology evolution and on the development of characterisation methods for graphene materials. In Core 2, we introduced a robust and authoritative Validation Service for materials and devices, vastly strengthened our standardisation activities, and began exploring market needs and opportunities for graphene and layered materials. These activities continue to expand in Core 3.

HIGHLIGHTS FROM 2020

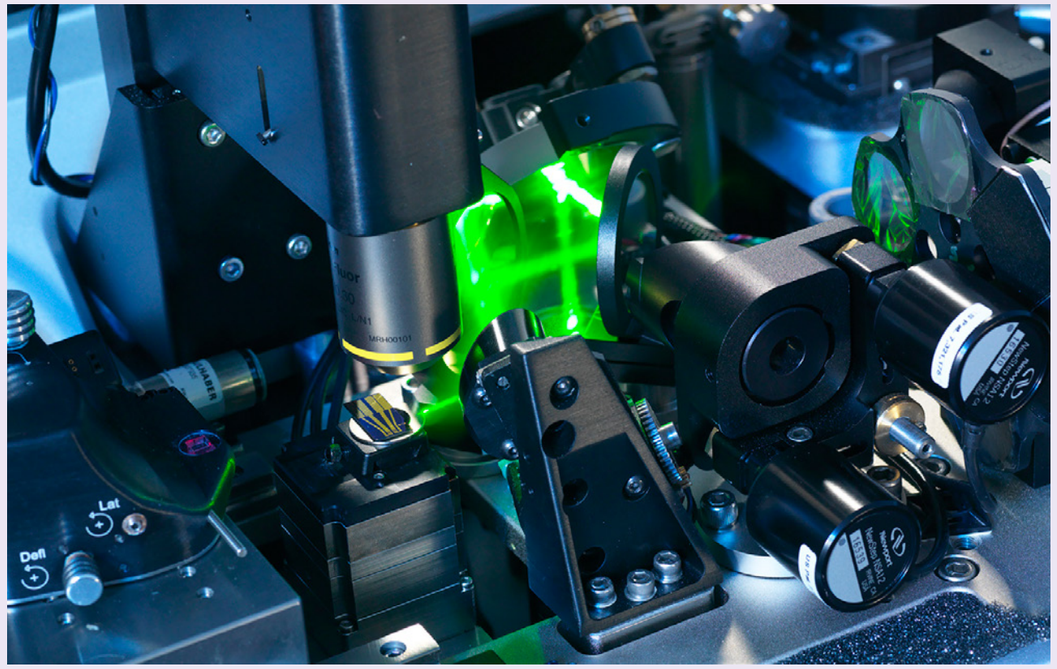
Over the past year, the Industrialisation Work Package continued to monitor the global landscape in order to identify windows of opportunity for Europe. The Graphene Technology and Innovation Roadmap team conducted an online survey among past focus investigation participants and the Graphene Flagship leadership to gather feedback and inform our decisions on future focus investigation formats and topics. In total, we received 135 completed responses, which represent an overall participation rate of about 51% across all qualified invitees.

The results include quantifiable feedback on the overall interests in our elaborate topic suggestions as well as numerous valuable insights submitted by the survey participants through voluntary free text options. They provide us with a complementary pillar for the selection of roadmap focus topics throughout Core 3. Taking into account this survey, as well as current trends in relevant markets, the forthcoming focus investigations in 2021 will cover the applications of graphene and layered materials in micro-electro-mechanical systems (MEMS), antibacterial and antiviral coatings, hydrogen technology and thermal management.

Selected results from the recent roadmap focus investigations formed the bases of two Graphene Roadmap Briefs that appeared in the IoP journal 2D Materials in January 2021. These form the initial issues for a continuous series of concise roadmap publications focusing on the status, progress and prospects of the industrialisation of graphene and layered materials in Europe and beyond. This illustrates our continuous efforts to enhance the communication of these materials’ industrial relevance to the scientific and broader community.

Industrialisation has also worked to create trust and confidence in GRMs by providing a professional world class Validation Service. In 2020, the service received 18 requests for validation and successfully delivered 15, despite restrictions on lab access due to the coronavirus pandemic.
The Graphene Flagship Standardisation Committee (GFSC) has worked to position Europe as a leader in innovation. The GFSC currently leads ten ongoing projects of different maturity levels in ISO and IEC. Four new Graphene Flagship Associated Members signed up specifically to work on standardisation projects with the GFSC.

We began a major upgrade of the Samples and Materials database, which will offer better alignment with standard taxonomy, as well as improved functionality.



Validating a graphene sensor at the National Physical Laboratory (NPL). Credit: NPL

POWERED BY THE GRAPHENE FLAGSHIP

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. For us, this community is an indispensable pool of expertise in everything we do, as well as being customers of our Validation Service and the Samples and Materials database.

SAILING FORWARD

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 the market and society. The Industrialisation Work Package will therefore also enable the Graphene Flagship to communicate its relevance in a convincing way.

Our 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. 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 layered materials).

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 Experimental Pilot Line, we expect the validation team to play a role in providing independent assessments 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.

The Graphene Flagship Standardisation Committee launched a Standardisation Certificate.

GRAPHENE SUCCESS STORIES

Five success stories from companies in the Graphene Flagship

One of the Graphene Flagship's most fundamental goals is to get new graphene-based products into the hands of consumers.

To this end, the Graphene Flagship coordinates research into graphene and layered materials at more than 170 institutions, both academic and industrial, across 22 countries in Europe. Not only this, but a third of our funding is devoted to eleven industry-focused Spearhead Projects, each directed by a leading company in the field – and we recently launched the 2D Experimental Pilot Line (2D-EPL) to integrate graphene and layered materials into semiconductor manufacturing, which could lead to new products for computing and wireless communication.

Our devotion to pushing forward the bounds of knowledge, combined with our focus on interdisciplinary collaboration, is why 15 spin-off companies and over 90 products have emerged from the Graphene Flagship since the start of the project in 2013. This number is ever on the rise.

Read on to learn about five successful companies in the Graphene Flagship consortium, and discover how their research takes graphene out of the lab and onto the European market.

BeDimensional VARTA Microinnovation

Enhancing lithium-ion batteries with graphene

BeDimensional is a spin-off from the Graphene Flagship and our partner institution the Italian Institute of Technology (IIT), Italy. They develop materials based on graphene and two-dimensional crystals for the manufacturing and energy industries. In 2020, they teamed up with IIT and the largest battery manufacturer in Europe, Graphene Flagship partner VARTA Microinnovation, to develop graphene-enabled silicon-based lithium-ion batteries.

Thanks to graphene, their new batteries have a 30% higher capacity than the currently available alternatives and can withstand over 300 cycles of use.

The Graphene Flagship helped to advance this prototype on several fronts. The first ideas for a graphene-enabled battery were sparked during the first phase of the project, and the spin-off BeDimensional was established to supply graphene material for the project. The team has now embarked on a new challenge: to develop a long-lasting sustainable graphene-enabled battery for electric vehicles. This is the goal of the Graphene Flagship Spearhead Project GrEEnBat.

The Graphene-XT team tested their graphene-based lubricating additive for motor oil in the high-intensity engine of a working Motocross motorcycle. Credit: Graphene-XT

15 spin-off companies and over 90 products have emerged from the Graphene Flagship since the start of the project in 2013. This number is ever on the rise."

INBRAIN Neuroelectronics

Developing neural implants to treat Parkinson's and epilepsy

Using smart devices based on an innovative graphene electrode, the Graphene Flagship spin-off INBRAIN Neuroelectronics aims to speed up the development of new graphene-based neural implants to help treat brain disorders like Parkinson's and epilepsy.

The company, now a partner of the Graphene Flagship, was established in 2019 by Graphene Flagship partners ICN2 and ICREA, Spain. They were awarded €1 million by key European investors to support their research,[1] and went on to win an additional €100,000 from Sabadell Bank in a competition against 145 other health-related start-ups and spin-offs.

INBRAIN's devices decode brain signals with high fidelity, and when paired with artificial intelligence, they could help doctors to determine the best course of action to treat patients. Now, in collaboration with the Graphene Flagship, INBRAIN engineers are testing their technology in large animals – and soon, Graphene Flagship partner the University of Manchester and other top institutions will begin tests in humans.

[1] Sabadell Asabys, Alta Life Sciences, Institut Català de Finances (ICF) and Finaves

Graphene-XT

Graphene-based lubricating oil for motorbikes and cars

Scientists at Graphene Flagship partner company Graphene-XT, Italy, developed a new graphene-based lubricating oil for diesel or petrol engines in cars and motorcycles. The team tested their lube in the high-intensity engine of a working motocross motorcycle, in a circuit not far from multiple MotoGP World Champion Valentino Rossi's ranch.

Due to its layered structure, graphene acts as a strong and effective lubricant. The atom-thin carbon layers easily slip and slide against each other with very little friction. By adding graphene to their lubricating engine oil, the team improved its performance and stability at high temperatures, reducing wear and tear on the engine. Moreover, all of these effects combined reduce engine noise and fuel consumption.

The team are hard at work on the launch of their first commercial lube product, which they expect will hit the market in the first half of 2021. The lube works in any thermal engine: on wheels, on water or in the air. Graphene-XT hopes to release many more commercial products in the future.

Graphene-based lubricating oil in action. Credit: Graphene-XT

das-Nano

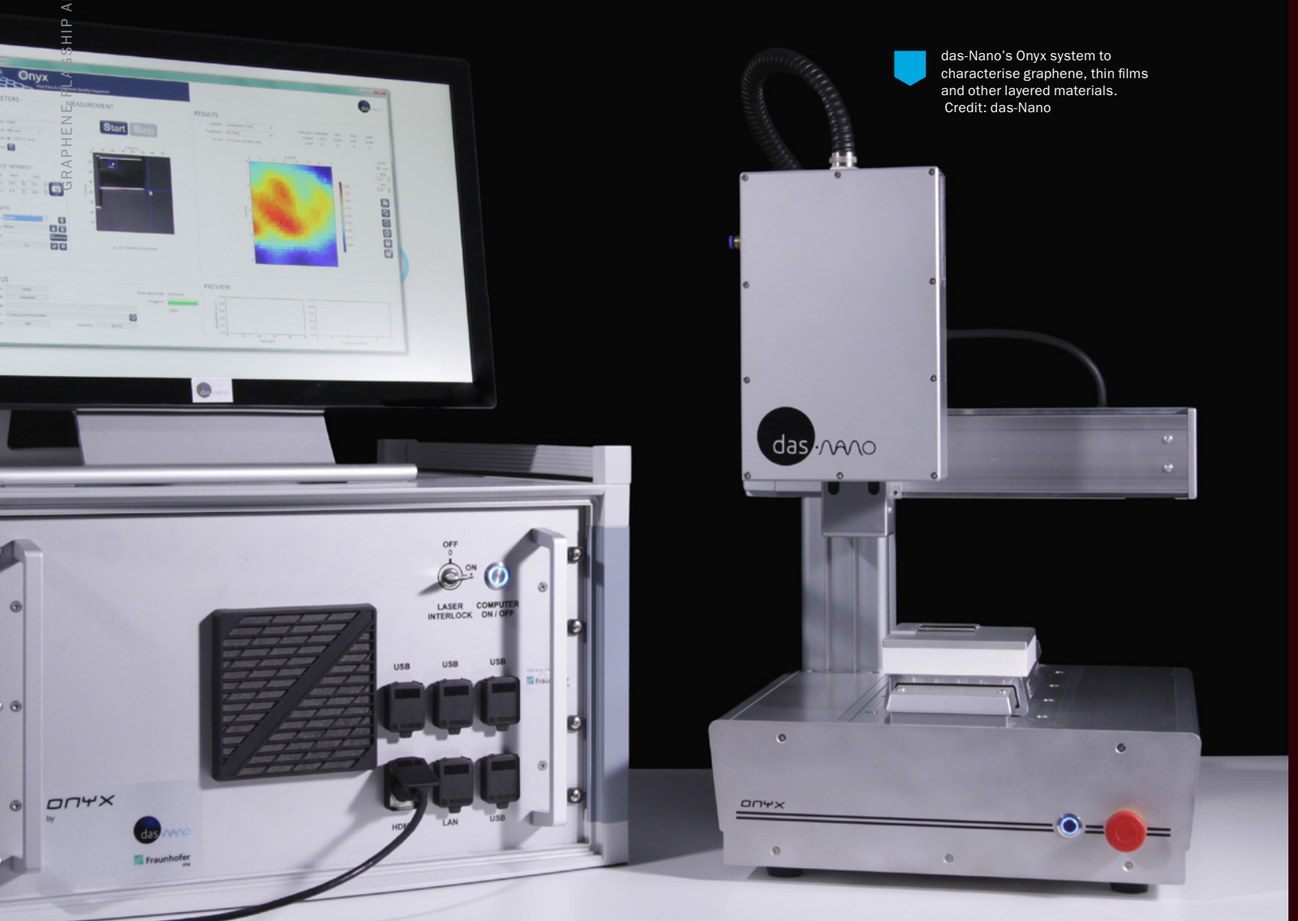
NON-DESTRUCTIVE CHARACTERISATION OF GRAPHENE AND LAYERED MATERIALS

A technology-focused SME and an Associated Member of the Graphene Flagship, das-Nano designs and manufactures Terahertz spectrometers for applications in the automotive and aeronautics industries, for wind power and advanced materials, and more. Their product Onyx is the first system on the market designed to provide full-area, non-destructive characterisation of graphene, thin films and other layered materials.

Onyx covers the gap between the macroscale and the nano-scale, characterising areas from millimetres squared to metres squared, accelerating the industrialisation of materials like graphene and layered materials. It can record spatial resolutions of a few hundreds of microns, enabling the fast characterisation of large sample areas – as opposed to typical microscopic methods like Raman and scanning electron microscopy.

Many companies are actively developing stronger, lighter and more durable composites using graphene additives. We expect to see new graphene composite products reach the market by 2021 to 2022, especially in areas like aerospace, rail transport, packaging and construction."

Nic Gowland
Graphene Flagship Business Developer



das-Nano's Onyx system to characterise graphene, thin films and other layered materials. Credit: das-Nano

Cambridge Raman Imaging

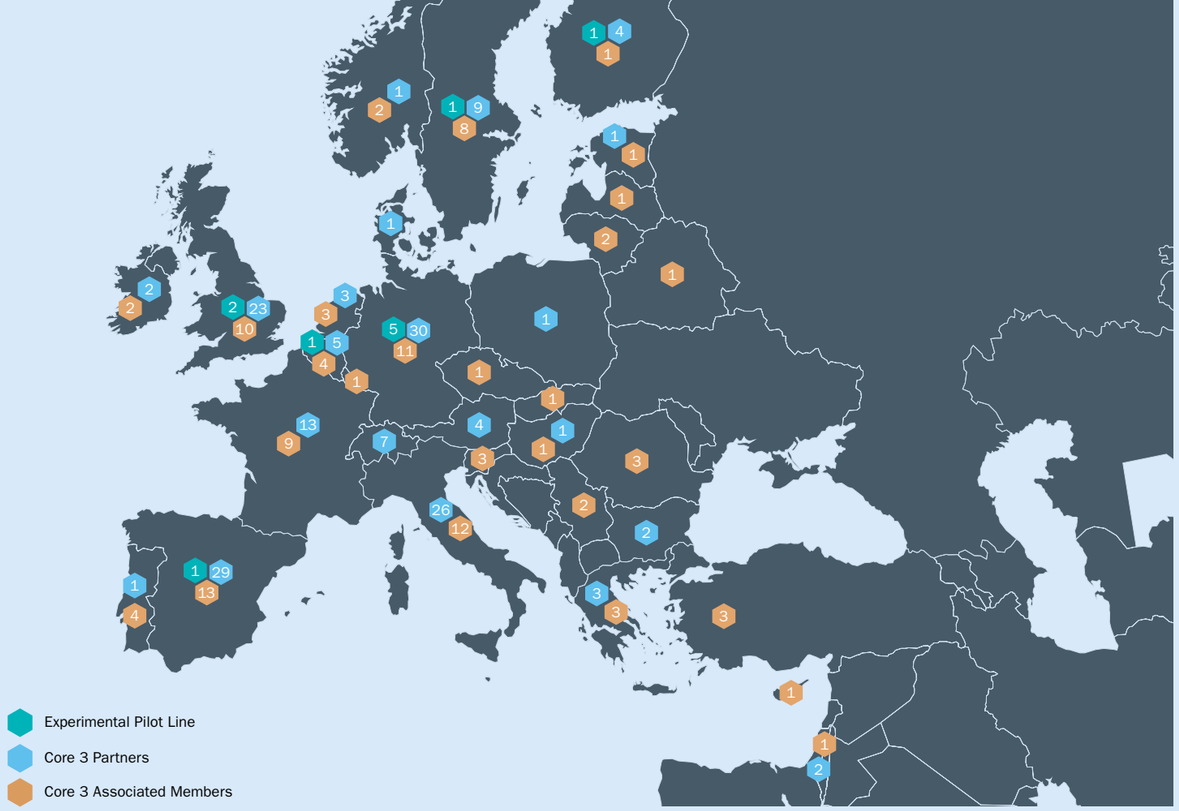
DEVELOPING A GRAPHENE-BASED ULTRAFAST LASER FOR A RAMAN MEDICAL MICROSCOPE

The scientists at Cambridge Raman Imaging, a new Graphene Flagship spin-off, are developing a graphene-based laser to generate images of tumours inside the body and track their growth or remission, among other applications. The spin-off was established by Graphene Flagship partners the University of Cambridge, UK, and the Polytechnic University of Milan, Italy, and they recently received an investment of €275,000 to support their developments.

Their team are working on a graphene-based ultrafast laser for a Raman microscope. The microscope will generate real-time digital images of tissue samples using Raman spectroscopy, differentiating between healthy and diseased tissue to show the extent of tumours and their responsiveness to treatments. This could also allow a surgeon to make sure a cancer has been completely removed after operation. Furthermore, thanks to the unique properties of graphene and layered materials, their device is based on two synchronised fibre-based 'picosecond' lasers: an architecture that is much cheaper than conventional solid-state systems.

2020 was a successful year for graphene in the biomedical sector, garnering the attention of investors and large pharmaceutical companies. Innovation is sailing forward at high-speed, especially for medical devices, so we expect to see more graphene technologies reaching clinical trials and the market soon."

Cinzia Spinato
Graphene Flagship Business Developer



Experimental Pilot Line

BELGIUM
- Interuniversity centre for micro-electronics – imec

FINLAND
- Technical Research Centre of Finland – VTT OY

GERMANY
- AIXTRON SE
- AMO GmbH
- Leibniz Institute of Innovative Microelectronics – IHP
- micro resist technology GmbH
- SUSS MicroTec GmbH

SPAIN
- Graphenea SL

SWEDEN
- Chalmers University of Technology

UNITED KINGDOM
- Aixtron Ltd
- Oxford Instruments Ltd

Core 3 Partners

AUSTRIA
- Guger Technologies OG
- Technical University of Vienna
- University of Natural Resources and Life Sciences, Vienna
- Varta Micro Innovation GmbH

BELGIUM
- Interuniversity Centre for Microelectronics – imec
- National Society of Aerospace Constructions – SONACA SA
- Toyota Motor Europe NV
- Catholic University of Leuven
- Free University of Brussels

BULGARIA
- Institute of Mechanics, Bulgarian Academy of Sciences
- Research and Development of Nanomaterials and Nanotechnology Ltd

DENMARK
- Technical University of Denmark

ESTONIA
- University of Tartu

FINLAND
- Aalto University
- Emberion OY
- Finnish Institute of Occupational Health AG
- Technical Research Centre of Finland – VTT OY

FRANCE
- Airbus Helicopters SAS
- National Centre for Scientific Research – CNRS
- Commission for Atomic and Alternative Energies – CEA
- European Science Foundation – ESF
- National Institute of Health and Medical Research – INSERM
- National Laboratory of Metrology and Testing – LNE
- NAWA Technologies
- Pixium Vision
- Polymem SA
- Thales
- University of Strasbourg
- University of Lille
- Sorbonne University

GERMANY
- Airbus Defence and Space GmbH
- BASF SE
- BMW AG
- Bundeswehr University Munich
- Christian-Albrechts University of Kiel
- Evonik GmbH
- Finisar GmbH
- Fraunhofer Society
- Friedrich-Alexander University of Erlangen-Nürnberg
- Friedrich-Schiller University of Jena
- AMO GmbH
- Infineon Technologies AG
- Interactive Wear AG
- Karlsruhe Institute of Technology
- Lufthansa Technik AG
- Max Planck Society for the Advancement of Science
- Multi Channel Systems GmbH
- Nokia Solutions and Networks GmbH
- Phi-Stone AG
- RWTH Aachen
- Siemens AG
- Singulus Technologies AG
- Sixonia Tech GmbH
- Technical University of Dresden
- Trevira GmbH
- University of Augsburg
- University of Bremen
- University of Regensburg
- University of Ulm
- Varta Micro Battery GmbH

GREECE
- Greek Foundation for Research and Technology – FORTH
- Hellenic Mediterranean University
- University of Ioannina

HUNGARY
- Centre for Energy Research, Hungarian Academy of Sciences – MTA EK

IRELAND
- Boston Scientific Ltd
- Trinity College Dublin

ISRAEL
- Mellanox Technologies Ltd
- Israel Institute of Technology – Technion

ITALY
- BeDimensional SpA
- Bioage SRL
- Breton SpA
- Bruno Baldassari & Fratelli SpA
- Fiat Research Centre SpA
- National Research Council – CNR
- Interuniversity National Consortium for Telecommunications – CNIT
- Dallara Automobiles SpA
- Enel Green Power SpA
- Graphene-XT SRL
- Greatcell Solar SRL
- Italian Institute of Technology – IIT
- Italcementi SpA
- Leonardo SpA
- Medica SpA
- Nanesa SRL
- Nokia Solutions and Networks SPA
- Polytechnic University of Milan
- International School for Advanced Studies – SISSA
- SPAC SpA
- STMicroelectronics SRL
- University of Padova
- University of Rome Tor Vergata
- University of Salerno
- University of Trieste
- University of Pisa

NETHERLANDS
- Delft University of Technology
- Eindhoven University of Technology
- University of Groningen

NORWAY
- CrayoNano AS

POLAND
- Lukasiewicz Research Network – Institute of Microelectronics and Photonics Polytechnic University of Warsaw

PORTUGAL
- University of Minho

SPAIN
- Airbus Operations SL
- Aernnova Aerospace SA
- ArcelorMittal SA
- Autonomous University of Barcelona
- Avanzare SL
- Barpimo SA
- Casals Cardona SA
- CIBER-BBN
- CIC biomaGUNE
- CIC energiGUNE
- CIC nanoGUNE
- DIPC
- FIDAMC Foundation
- Tecnalia Foundation
- Graphenea SL
- Grupo Antolin SA
- ICFO
- ICN2
- IDIBAPS
- IMDEA Nanociencia
- Inbrain Neuroelectronics SL
- INTERQUIMICA
- INIA
- Naturality
- Qurv Technologies SL
- Spanish National Research Council – CSIC
- University of Madrid – Carlos III
- University of Castilla-La Mancha
- University of Zaragoza

SWEDEN
- ABB AB
- Chalmers Industrial Technology
- Chalmers University of Technology
- Ericsson AB
- Graphmatech AB
- Karolinska Institute
- NanOsc AB
- Umeå University
- Veoneer Sweden AB

SWITZERLAND
- CONFINIS AG
- EMPA
- Schaffhausen Institute of Technology AG
- University of Zurich
- University of Geneva
- Swiss Federal Institute of Technology in Lausanne – EPFL
- Swiss Federal Institute of Technology in Zurich – ETH

UNITED KINGDOM
- Aixtron Ltd
- Amalyst Ltd
- Cambridge Raman Imaging Ltd
- Composites Evolution Ltd
- Emberion Ltd
- FlexEnable Ltd
- Icon Lifesaver Ltd
- Imperial College London
- M-Solv Ltd
- Nokia Solutions and Networks Ltd
- Novalia Ltd
- National Physical Laboratory – NPL
- Printed Electronics Ltd
- Prognomics Ltd
- Queen Mary University of London
- University of Cambridge
- University of Manchester
- University of Nottingham
- University of Sheffield
- University of Warwick
- University College London
- University of Lancaster
- Versarien plc

Core 3 Associated Members

BELARUS
- Belarusian State University

BELGIUM
- Ampashield NV
- University of Liège
- University of Mons
- University of Namur

CYPRUS
- Delta Nano Ltd

CZECH REPUBLIC
- Palacký University of Olomouc

ESTONIA
- SCALE Nanotech

FINLAND
- University of Eastern Finland

FRANCE
- 2CRSi
- BLACKLEAF
- ENS Paris Saclay – Aimé Cotton Laboratory
- EDF
- European Synchrotron Radiation Facility – ESRF
- Grapheal
- Materials and Engineering Laboratory, Grenoble Institute of Technology
- Synchrotron Soléil
- University of Montpellier

GERMANY
- Dräger Safety AG
- Free University of Berlin
- International Standards Consulting GmbH
- Jülich Research Centre GmbH
- Ludwig Maximilians University
- Mjr Pharmjet GmbH
- Namlab GmbH
- Helmholtz Centre for Materials and Energy – HZB
- SURAGUS GmbH
- TALGA GmbH
- University of Hamburg

GREECE
- National Centre for Scientific Research Demokritos
- OTENET
- University of Patras

HUNGARY
- Budapest University of Technology and Economics

IRELAND
- Optrace Ltd
- Technological University of Dublin

ISRAEL
- Bar Ilan University

ITALY
- ENEA
- Fortore Energia SpA
- GSNET SRL
- Luigi Bandera SpA
- Optosmart SRL
- Sacred Heart – Catholic University
- Tetra Pak SpA
- University of Palermo
- University of Cagliari
- University of Bologna
- University of Rome Sapienza
- Vittoria SpA

LATVIA
- University of Latvia

LITHUANIA
- Centre for Physical Sciences and Technology – FTMC
- TERAVIL Ltd

LUXEMBOURG
- OCSIAL Sarl

NETHERLANDS
- Maastricht University
- Institute of Molecules and Materials, Radboud University
- University of Twente

NORWAY
- Abalonyx AS
- Elkem AS

PORTUGAL
- Graphenest
- Sphere Ultrafast Photonics
- University of Aveiro
- University of Porto

ROMANIA
- Ioan Ursu Institute of Physics, Bolyai University
- EPI-SYSTEM SRL
- Transylvania University of Brasov – UTBV

SERBIA
- Dirigent Acoustics
- Institute for Chemistry, Technology and Metallurgy – ICTM

SLOVAKIA
- Slovak Academy of Sciences

SLOVENIA
- Faculty of Information Studies Novo Mesto
- University of Ljubljana
- University of Nova Gorica

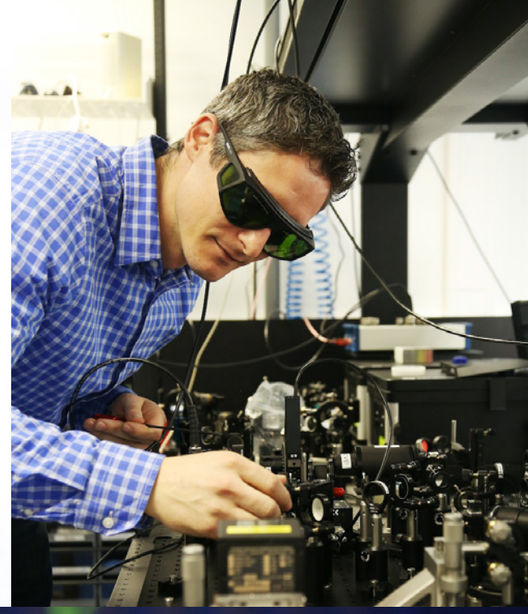
SPAIN
- AIMPLAS
- ALBA-CELLS
- Autonomous University of Madrid
- CIDETEC
- Complutense University of Madrid
- das-Nano SL
- Gnanomat SL
- Lotus Partners
- Regemat3D SL
- Textile Research Institute – AITEX
- University of Alicante
- Centre for Research in Biological Chemistry and Molecular Materials, University of Santiago de Compostela – CIQUS
- University of the Basque Country

SWEDEN
- APR Technologies
- GRAFREN AB
- Graphensic
- Karlstad University
- Royal Institute of Technology – KTH
- Linköping University
- SenseAir AB
- Uppsala University

TURKEY
- Boğaziçi University
- Izmir Institute of Technology
- Integrated Manufacturing Technologies Research and Application Centre, Sabanci University

UNITED KINGDOM
- Atomic Mechanics Ltd
- CamGraPhIC Ltd
- First Graphene Ltd
- Footfalls & Heartbeats Ltd
- Graphitene Ltd
- Haydale Ltd
- Nu Quantum Ltd
- Payper Technologies Ltd
- University of Brighton
- University of Exeter

THE VOYAGE AHEAD



A closing statement from the Science and Technology Officer

The first year of the Graphene Flagship's Core 3 phase was challenging for everyone involved due to the coronavirus pandemic.

This brought to light an urgent need to devise new technologies to protect the human body from its immediate environment. Graphene and layered materials are promising candidates for the design of a novel generation of surfaces to help deal with the daily challenges posed by the coronavirus, as well as similar future diseases.

We recognised that it is vital for the Graphene Flagship, as one of the largest European Science and Technology projects, to make use of all of its collective and accumulated knowledge to fight the current pandemic, as well as those that may come in the future. To this end, we launched a targeted and multidisciplinary Working Group, comprising companies and researchers from across the consortium. The group's ultimate objective is to exploit the potential of graphene and layered materials in order to contribute to the global front against this unprecedented societal challenge.

Indeed, several industrial and academic partners of the Graphene Flagship have already contributed in different ways to the fight against the pandemic.

I am pleased that the European Commission has extended Core 3 to the end of September 2023. The extension will ease the impact of the coronavirus on our progress in science and technology innovation. This means that, from the start of the Graphene Flagship ramp-up phase on 1 October 2013, ten years will have passed by the end of our Horizon 2020 funding.

As we approach our tenth year, I look back to the pilot proposal we submitted back in October 2010, and the roadmap we produced as a result. It is amazing to see how we fulfilled our promises: not just in terms of fundamental science and high impact publications, but, most notably, in terms of technology readiness level and innovation.

Every year, new patents are applied for and granted, new start-ups and spin-off companies are established, and new products reach the market. While the production of large quantities of graphene and layered materials based on liquid-phase exfoliation methods has already firmly reached the industrial scale, in terms of applications, the past year has seen a significant increase in efforts to integrate these materials at the wafer scale. Graphene Flagship scientists have demonstrated a number of devices, ranging from detectors to modulators, imagers, sensors and transceivers, at the wafer scale. We are on the verge of graphene integration into fabrication, and process design kits should be available by the end of Core 3.

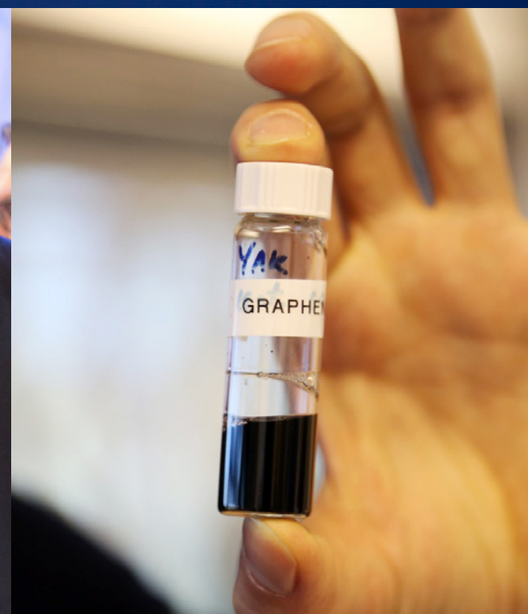
The Graphene Flagship also strives to accelerate the reliable, sustainable and safe production of graphene and layered materials, satisfying the specific needs of different application areas. Our scientific and technological results contribute to the United Nations' Sustainable Development Goals and the EU Green Deal. The Graphene Flagship boosts European economic growth by creating new jobs, strengthening competitiveness and developing investment opportunities. Conscientious hiring, purchasing and waste disposal practices also ensure that our research meets goals related to gender equality, sustainable economic growth and production patterns.

The market capitalisation of Graphene Flagship partners and Associate Members, commercialising graphene and layered materials or products related to them, already far exceeds the direct cash contribution to-date from the European Commission. This confirms the excellent value-for-money of the European Commission's investment in the Graphene Flagship.

I am also pleased that the work of the Graphene Flagship will continue in Horizon Europe, with a first set of new coordination, support, research and innovation action calls already opening at the end of 2021.

This is no time to rest. We still have a long journey ahead in our voyage together.

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. The Graphene Flagship gathers over 170 academic and industrial partners from 22 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.

With an additional €20 million investment, the European Commission has now funded the creation of an Experimental Pilot Line for graphene-based electronics, optoelectronics and sensors.

Funded by
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