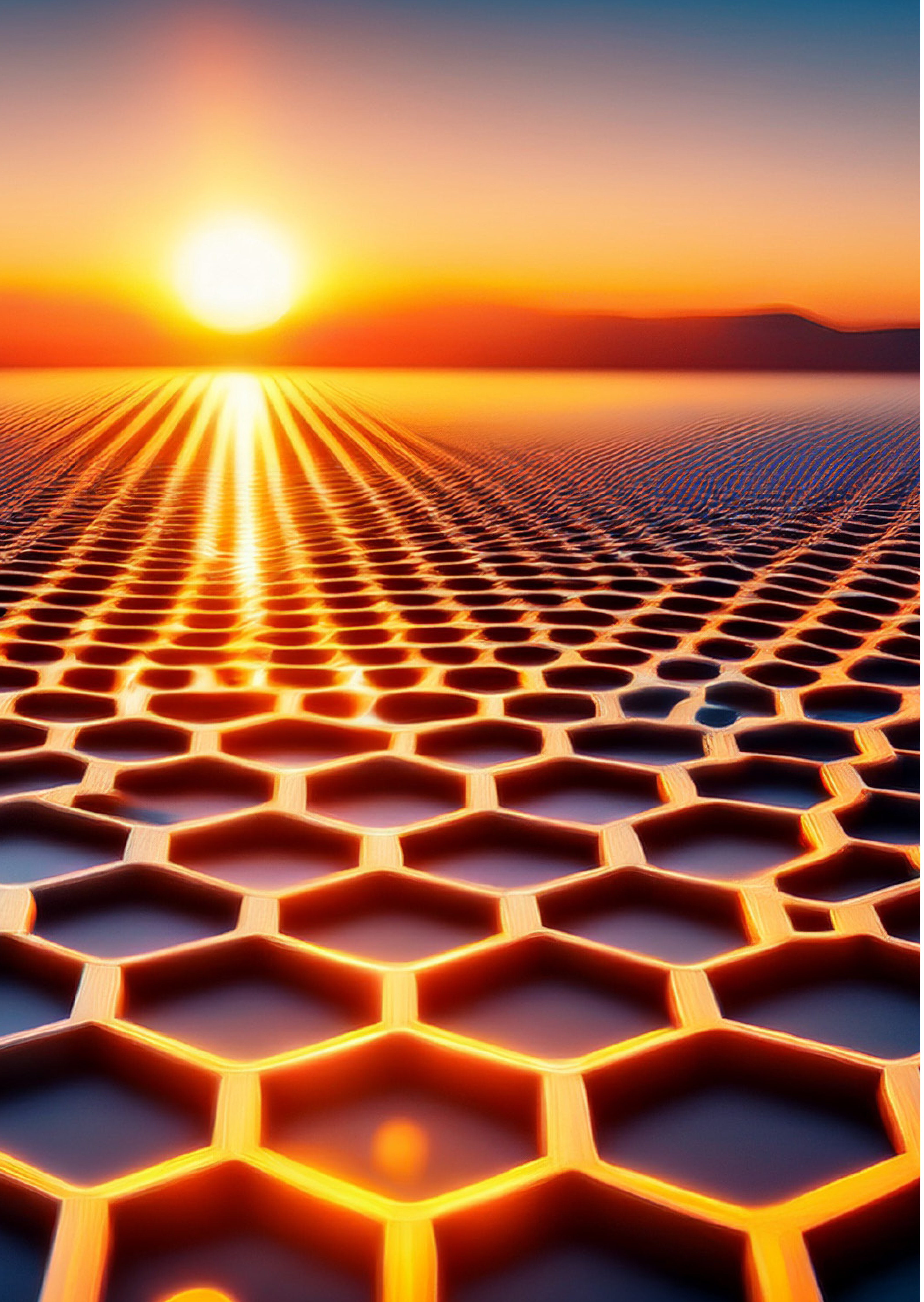
GRAPHENE FLAGSHIP

Annual Report 2025

Funded by the European Union



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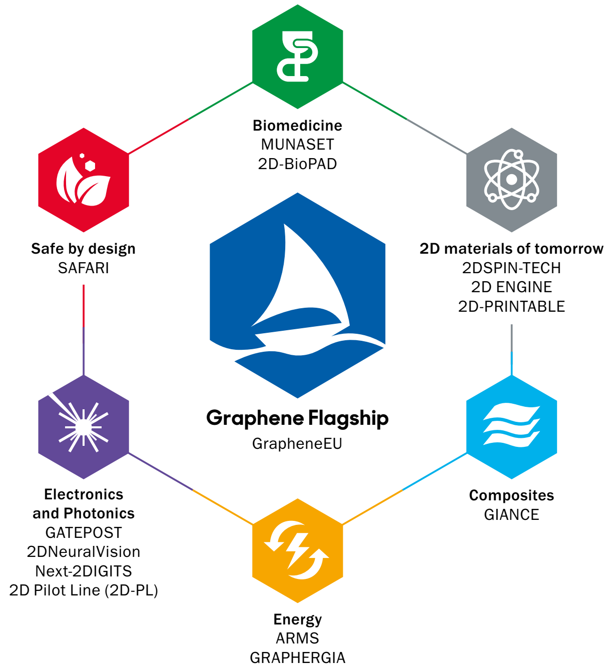

MEET THE FLAGSHIP
Bringing together 126 academic and industrial partners across 14 projects, the Graphene Flagship continues to advance Europe's lead in technologies that rely on graphene and other 2D materials.

From the Director

AT THE TIME of writing this, it is almost exactly a year since I took over the position as Director of the Graphene Flagship from Patrik Johansson. And what a year it has been! So many new experiences – events, acquaintances, communities, working groups and a much deeper insight into all the activities going on in our community. Most importantly, a lot of thought has been given to where we are headed in the future.

> Over the past year, the Graphene Flagship has continued to demonstrate the value of coordinated, long-term, research efforts all over Europe.

Over the past year, the Graphene Flagship has continued to demonstrate the value of coordinated, long-term, research efforts all over Europe. As usual, the community has delivered a strong portfolio of scientific outputs, from advances in scalable graphene and 2D-material synthesis to increasingly mature device demonstrators in sensing, energy, electronics and health. This underlines one of our central achievements: the ability to connect world-class materials science with systems-level engineering and application-focused development. On this note, I think it should be mentioned that during 2025 two new technical specifications relating to graphene from the International Organisation for Standards (ISO) were published. It may not sound that exciting, but it is very important.

Collaboration remains at the heart of the Graphene Flagship's success. We bring together many different organisations and competencies, allowing problems to be addressed end-to-end. At our events, training actions and dissemination activities continued to play a crucial role in supporting the community, particularly early-career researchers and SMEs, and in ensuring that knowledge generated within projects is shared broadly and efficiently. But, as the European landscape is changing, collaboration beyond the Graphene Flagship community is equally important. We have spent a lot of time this year, shaping our input to position papers, taking part in European level workings groups and more. Why? Because it is important that we are an active and well-articulated voice in Europe, both to make sure that graphene and related 2D materials are not overlooked, and because this community knows how to bring an innovative, advanced material to market.

Looking ahead, I see both strong momentum and important transitions on the horizon. Europe is heading into a new framework programme, and the political scene in the world is changing fast. We need to be as adaptive as always, and we will benefit from having built a strong community, able to both identify and address new challenges as they appear. Therefore, the coming year will be defined by consolidating the community while continuing to identify new application areas where 2D materials can deliver added value. What comes next is not a single programme, but a legacy: a mature European ecosystem, ready to integrate graphene and related materials into future Horizon Europe initiatives, industrial partnerships and societal solutions.

Maria Abrahamsson
Graphene Flagship Director

GRAPHENE FLAGSHIP ANNUAL REPORT 2025

Graphene Flagship: Building a European ecosystem for integrating 2D materials

THE GRAPHENE FLAGSHIP is one of Europe's largest research and innovation initiatives, launched by the European Union in 2013 to advance graphene and related two-dimensional (2D) materials from scientific discovery to industrial application. With an initial €1 billion investment and continued support through programmes such as Horizon Europe, the initiative brings together 126 academic and industrial partners and 53 Associated Members. Its core mission is to translate Europe's scientific leadership in graphene and 2D materials into real-world technologies, strengthening Europe's position in advanced materials while supporting innovation, competitiveness and strategic autonomy.

At its heart, the Graphene Flagship operates as an innovation ecosystem spanning the entire value chain – from fundamental materials research to device development, manufacturing and system integration. Through coordinated research projects and shared infrastructure, it accelerates the development of applications in areas such as electronics, photonics, energy, composites and biomedical technologies. By connecting universities, research institutes and industry partners, the initiative helps transform promising laboratory discoveries into scalable technologies and commercial opportunities.

Equally important is the Graphene Flagship's role in building and sustaining Europe's 2D materials community. Over more than a decade, it has created a collaborative platform that connects hundreds of researchers, engineers, companies and innovators across countries and disciplines. Through coordinated research programmes, shared facilities, networking activities and industry engagement, the initiative has helped establish a cohesive European ecosystem for graphene and related materials – strengthening collaboration, knowledge exchange and the development of new talent across the field.

> Over more than a decade, it has created a collaborative platform that connects hundreds of researchers, engineers, companies and innovators across countries and disciplines.

For Europe, the value of the Graphene Flagship is both technological and strategic. Graphene and other 2D materials have the potential to enable breakthroughs in sectors critical to Europe's competitiveness, including next-generation electronics, lightweight materials for sustainable transport and advanced energy technologies. By aligning scientific excellence, industrial innovation and a strong collaborative community, the Graphene Flagship ensures that Europe not only leads in the discovery of these materials but also in translating them into sustainable technologies that support the EU's digital, industrial and green transitions.

BUILDING A COMMUNITY

The strength of the Graphene Flagship is its ability to bring together experts from across the 2D materials ecosystem to collaborate on groundbreaking work. The format of the initiative facilitates knowledge exchange, fosters collaboration within and beyond European funded projects and addresses issues of common interest to the community. The Graphene Flagship uniquely represents and strengthens Europe's 2D materials community providing it with a voice and bridging the gap to related initiatives in Europe and beyond.

The Graphene Flagship's Association Mechanism opens the doors to broader connections beyond the research projects individual consortia, allowing both individual institutions to connect to the initiative and its projects as well as other EU- and national-funded projects. This allows for more diverse perspectives and wider opportunities for future collaborations.

The annual Graphene Week conference provides a home for this community, an opportunity for experts from the full 2D materials ecosystem to come together in person to discuss critical topics, network and explore future opportunities. This event has grown beyond a scientific conference, with sessions on cross-cutting topics, an Innovation Forum to encourage discourse between academia and industry and international workshops highlighting cooperation between Europe and other countries with strong contributions to 2D materials research and innovation.

Graphene Week is a great opportunity for the Graphene Flagship leadership to connect in person. Credit: Giò Tarantini/ Gruppo Tonello

CONTINUED INDUSTRIAL OUTPUT

Over the past decade and a half, the Graphene Flagship has successfully driven the commercialisation of 2D materials in Europe. Spinoffs born of the Graphene Flagship continue to drive key innovations in Europe, from graphene producers like BeDimensional and Sixonia to those championing specific applications from InBrain's brain sensors to Emberion's infrared cameras.

A new spinoff from the spearhead project AEROGrAFT, AERO MATERIALS, made its debut at Graphene Week 2025 showcasing their ultra-light nanomaterial for applications from filtration to optics as well as actuation and electromagnetic shielding.

Larger companies continue their work toward commercial products launched in the Graphene Flagship spearhead projects. In the past year, Medica released their In-Line Graphil graphene water filters capable of removing emerging contaminants such as PFAS, heavy metals, antibiotics, and pesticides due to the increased adsorption capacity of graphene oxide.

Furthermore, public and private investments in graphene technologies continue to add up. BeDimensional announced a €20 million EIB venture capital investment at the end of 2024, and nearly €5.5 million in national and European grants were awarded to Versarien, AIXTRON and Graphmatech in 2025.

PARTNERING FOR THE FUTURE

In preparation for the launch of a new public-private partnership with the European Commission, Innovative Advanced Materials for Europe (IAM4EU), the Graphene Flagship has joined forces with other associations to create the Innovative Advanced Materials Initiative (IAM-I). Representatives of the Graphene Flagship community help to guide the association on issues related to 2D materials.

Building on the work done over the past year-and-a-half, the first general assembly of IAM-I was held in Brussels in January 2025. Graphene Flagship partners and associated members participated in the election process and several representatives were elected in the Executive Board and Association Delegation, giving the Graphene Flagship a strong voice within the IAM-I governance. Notably, Gianluca Fiori, University of Pisa, former Division leader in the Graphene Flagship's Core 3 project, was elected VP-Research, with responsibility for the IAM-I budget. These groups also make up the Partnership Board where the European Commission is also represented.

Following this election, the IAM-I Working Groups and Task Forces were created. Graphene Flagship representatives were elected to lead several of these groups, contributing to defining the Strategic Technology Fields (STFs) for the future IAM4EU Strategic Research and Innovation Agenda (SRIA) and giving a strong voice and representation to the 2D materials community.

The Graphene Flagship Coordination Board met at Graphene Week 2025 in Vicenza, Italy. Credit: Giò Tarantini/ Gruppo Tonello

Jörg Radnik, as the task leader for standardisation and regulation within GrapheneEU, also serves as the co-leader of IAM-I's Task Force #2 "Standards and Norms." The challenges and needs related to standardisation in Europe have recently been identified through a survey in which project partners actively participated. Through the participation of additional project partners in the task force, as well as through the discussions within the standardisation committee, it is ensured that the Graphene Flagship actively contributes to shaping the standardisation and regulation of advanced materials in the future.

In December the Graphene Flagship prepared a common position on the Advanced Materials Act to support the community in responding to a European Commission call for evidence and public consultation. The Graphene Flagship advocates for a strong European policy framework to unlock the full potential of Advanced Materials, with graphene and 2D materials as key enablers of industrial competitiveness and sustainability. The document promotes a specific definition of Advanced Materials and emphasises the need for the Advanced Materials Act to support commercialisation, circularity and strategic autonomy through long-term investment, shared pilot facilities and SME support. By integrating 2D materials into critical technologies, the Advanced Materials Act can accelerate innovation, strengthen Europe's resilience and drive the twin green and digital transitions.

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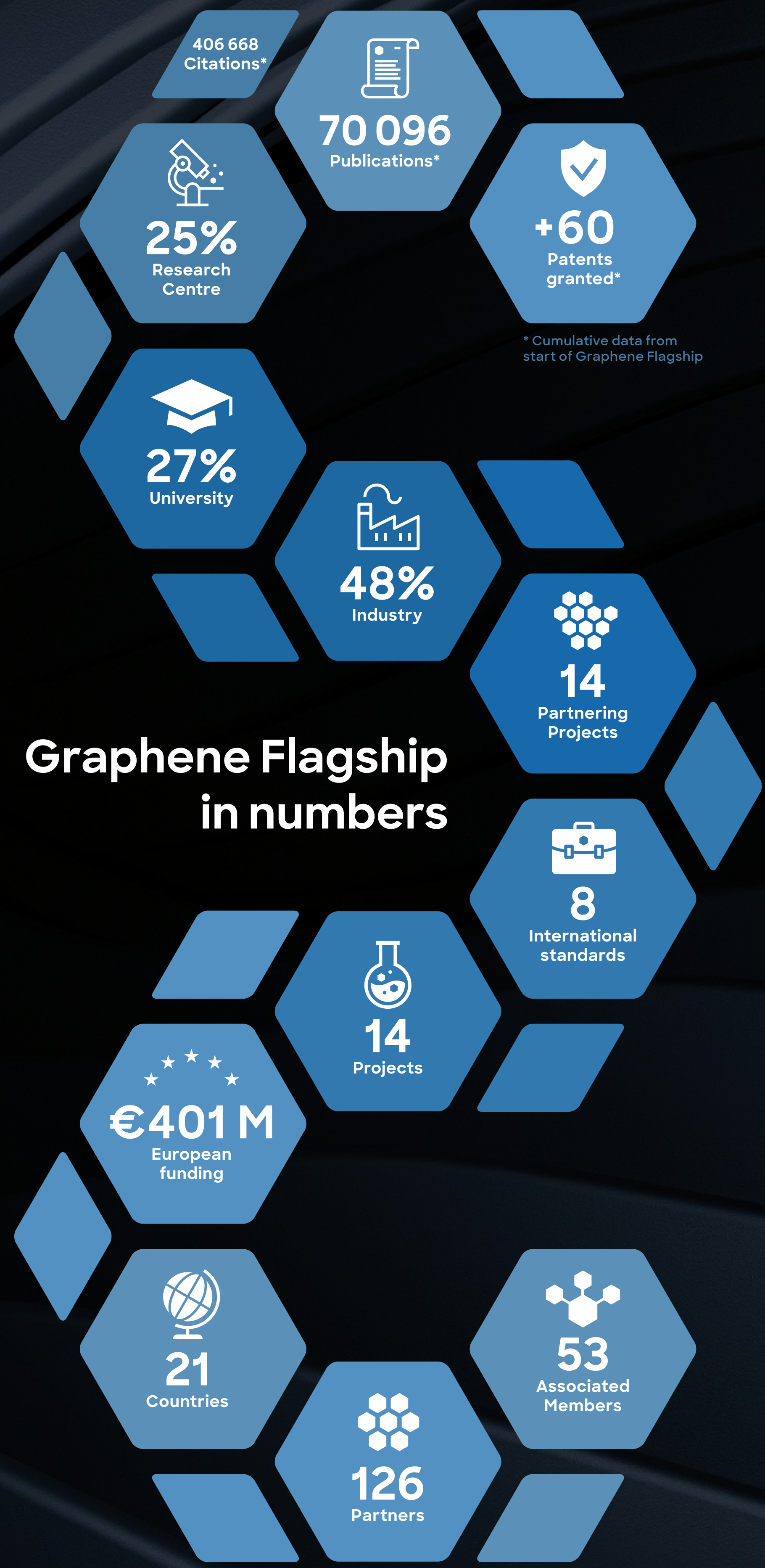
Graphene Flagship in numbers



Graphene Week

The home of Europe's 2D materials community

Each year Graphene Week gathers experts in graphene and 2D materials to share the latest breakthroughs, network and explore future collaborations. The conference celebrated its twentieth edition in Vicenza, Italy.
Photos by Giò Tarantini/ Gruppo Tonello

GrapheneEU

Providing coordination and support to the Graphene Flagship projects

THE GRAPHENE EUROPE in the Lead (GrapheneEU) coordinating and support action (CSA) serves as a hub for the Graphene Flagship projects' cross cutting actions. It ensures a strong and coherent initiative by providing key support functions in coordination and governance, industrialisation, dissemination and European and International alignment. The CSA accomplishes this by organising joint actions and managing a series of cross-project working groups to further the core Graphene Flagship objectives.

> This year, we advanced collaboration, innovation and standardisation across Europe's graphene and 2D materials community, reinforcing the Graphene Flagship's role as a global leader in next-generation materials."

Maria Abrahamsson
Chalmers University of Technology

PROGRESS IN 2025

Over the past year, the Graphene Flagship strengthened Europe's position as a global leader in graphene and 2D materials. Through strategic coordination, dissemination, community building, innovation support, standardisation and roadmapping, GrapheneEU delivered tangible impact across research, industry and policy. By fostering collaboration within Europe and internationally, it continues to shape the future of advanced materials innovation, supporting sustainable economic growth and global technological leadership.

Coordination and Governance
Work package one played a central role in coordinating the Graphene Flagship, supporting governance, and fostering knowledge exchange. The Director, Coordination Board, Partnership Coordination Committee, Project Managers Network and REACH/ECHA committee collectively enabled strategic decision-making, ensuring the initiative remains aligned with its ambitious goals.

Work package one also organised the Science and Technology Forum (STF), which contributed to shaping the Graphene Flagship's position on the 2026–2027 Horizon Europe Work Programme. In addition, it monitored developments in the European Advanced Materials regulatory landscape and prepared a comprehensive response to the Advanced Materials Act consultation. Through workshops, the Annual Meeting and dedicated fora, this work package strengthened connections across the community, helping projects share challenges and solutions while promoting collaboration among both new and established members.

European and International Alignment
The Graphene Flagship's outreach extends far beyond its core projects. GrapheneEU's work package two works to unite Europe's diverse graphene and two-dimensional (2D) materials community, fostering collaboration across academia, research organisations and industry. In 2025, the Association Mechanism successfully welcomed several new partners, bringing the total to 14 Partnering Projects and 53 Associated Members from 18 European countries. These members represent a wide spectrum of the 2D materials ecosystem, including universities, research institutions, SMEs and multinational corporations. Their contributions were celebrated at Graphene Week 2025, highlighting synergies between Associated Members and Graphene Flagship activities.

Work package two also strengthened international collaboration. Notably, the 9th EU-Korea Workshop in Strasbourg reinforced long-standing partnerships with the Korean Graphene Society, reflecting the Graphene Flagship's commitment to building a globally connected research community. By linking Europe's academic, industrial and research stakeholders, this work package enhances scientific collaboration, innovation and Europe's long-term leadership in 2D materials.

Dissemination
In 2025, work package three strengthened the visibility and impact of the Graphene Flagship by connecting researchers, innovators, and industry across Europe and beyond. Through its website, social media channels, press releases, and a quarterly newsletter, work package three ensured wide dissemination of the projects' achievements, scientific advances and Graphene Flagship initiatives. Social media engagement grew significantly, with over 662,000 users reached and a marked increase in interactions, highlighting the effectiveness of coordinated campaigns, including a series of posts highlighting Women in STEM.

Work package three also organised Graphene Flagship events including its annual conference, Graphene Week, early career workshops and the Diversity in Graphene mentoring programme. These events support knowledge sharing, inclusivity and collaboration across the 2D materials community.

Graphene Week 2025
The 20th edition of Graphene Week was held in Vicenza, Italy in September 2025. The event brought together 400 participants from 41 countries, including researchers, innovators and industry leaders, to celebrate achievements, showcase breakthroughs and catalyse future discoveries in the 2D materials field. Nearly 80% of participants were from Europe, reflecting the region's leading role in advancing graphene research, and a 33% female participation rate highlighted the Graphene Flagship's commitment to diversity and inclusivity.

Graphene Week 2025 featured over 200 presentations, 150 posters, workshops and panels covering applications from biomedicine and health to electronics, photonics, and composites. Special sessions – including the European Commission panel, the Open Forum and the Associated Members' impact session – highlighted collaboration across Graphene Flagship projects and the wider 2D materials ecosystem. The Innovation Forum and exhibition connected startups, industry and academic pioneers, showcasing commercially promising breakthroughs and the 2D Pilot Line value chain. Early-career researchers benefited from mentorship, knowledge-transfer and poster awards, supporting the next generation of scientific leaders.

Beatriz Alonso from Graphenea S.A. explains the needs of small and medium enterprises in standardisation. Credit: Giò Tarantini/ Gruppo Tonello

The GrapheneEU board met at Graphene Week 2025 in Vicenza, Italy. Credit: Giò Tarantini/ Gruppo Tonello

By combining world-class science, international participation and a focus on sustainability and inclusivity, Graphene Week 2025 reinforced Europe's global leadership in graphene and 2D materials and provided a vital platform for collaboration across research, innovation and industry.

Through its coordinated media coverage, digital outreach and high-profile events, work package three has reinforced the Graphene Flagship's role as a visible, collaborative and globally recognised initiative, supporting Europe's leadership in graphene and 2D materials innovation.

Industrialisation support
Innovation
Innovation remains a cornerstone of the Graphene Flagship. The Innovation Forum, held during Graphene Week 2025 in Vicenza, Italy, showcased the commercialisation potential of 2D materials across three days of discussions, pitch sessions and networking. Start-ups and established companies alike shared their successes and challenges, while experts offered practical guidance on raising capital and bringing products to market.

Beyond the Forum, the Graphene Flagship inspired the next generation of engineers through IGE-Day ("Introduce a Girl to Engineering"), promoted its work at the Swedish Graphene Forum and participated in international events such as the I2DM2025 Summit & Expo in Abu Dhabi.

The Innovation Working Group, composed of representatives from all Graphene Flagship projects, meets regularly to coordinate workshops, share best practices and foster collaboration. Team members also engage with external platforms like AI4AM, Graphene 2025, London Business School's Festival of Minds and the ASCEND Innovation Conference to exchange knowledge and promote industrial adoption of graphene-based technologies.

Standardisation
In 2025, the Graphene Flagship made important strides in standardisation, with two key international standards published:
- **ISO TS 9651** – Classification of graphene-related 2D materials
- **ISO TS 23359** – Chemical characterisation of graphene/rGO/GO flakes

These standards provide clear, uniform descriptions of 2D materials, simplifying trade, ensuring quality and supporting industrial uptake. Workshops at Graphene Week highlighted the need for standards tailored to manufacturing environments, emphasising practical applications for quality control during production. The Graphene Flagship's standardisation committee continues to serve as a forum where projects can provide input and stay updated on developments, ensuring alignment between research and industrial requirements.

Roadmapping
The roadmap team continued to guide the Graphene Flagship's long-term vision for graphene and related 2D materials. Four roadmap working group meetings in 2025 facilitated methodological refinement, knowledge exchange and alignment across projects. These interactions fostered a collaborative atmosphere, encouraging projects to coordinate objectives and share best practices.

Projects were supported with structured materials and online resources to ensure continuity and clarity, with an emphasis on:
- **Integrating** value-chain perspectives to identify innovation opportunities
- **Engaging** end-users early to ensure market relevance
- **Focusing** on scalable applications
- **Promoting** inter-project collaboration to maximise impact

CSA management
Work package five managed internal operations, governance and quality control for GrapheneEU. This work package coordinated the first CSA review with the European Commission, monitored community interactions and ensured timely submission of contractual deliverables. The team also assisted in harmonising reviews for 14 Graphene Flagship projects, enabling consistent evaluation and follow-up across the initiative.

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POWERING THE GRAPHENE FLAGSHIP
With 14 projects under its umbrella, the Graphene Flagship thrives on collaboration and community. GrapheneEU plays a vital role in connecting new 2D materials researchers and innovators with the existing Graphene Flagship network. Through instruments like the Association Mechanism and expert committees such as REACH/ECHA, past and present projects share knowledge and experience, ensuring continuity, cross-topic collaboration and a strong, united community driving Europe's leadership in graphene and 2D materials.

ON THE HORIZON
In 2026, GrapheneEU will continue fostering high-level dialogue and maintaining community cohesion, particularly engaging RIA/IA projects concluding their work to preserve continuity. Innovation activities will intensify, with pitch training, go-to-market workshops and the annual Graphene Week in Porto remaining central to supporting research, collaboration and commercialisation.

Standardisation efforts will focus on "bringing standards to the factory" and expanding beyond graphene to other 2D materials. Roadmapping will move into integration mode, synthesising project-level contributions into a coherent Graphene Europe roadmap, with a first draft in March, internal circulation in June, and submission to the European Commission in August.

PARTNERS
Chalmers University of Technology, Sweden
Chalmers Industriteknik, Sweden
European Science Foundation, France
University of Cambridge, United Kingdom
Fraunhofer Institute for Systems and Innovation Research ISI, Germany
Bundesanstalt für Materialforschung und – prüfung (BAM), Germany

PARTNERING PROJECTS
SIO Grafen

ASSOCIATED MEMBERS
Spanish National Research Council (CSIC),
Material Science Institute of Madrid
Italian Institute of Technology
AREAVISIONTECH
Ericsson Research
Constructor Group AG

The Science and Technology Forum contributed to shaping the Graphene Flagship's position on the 2026–2027 Horizon Europe Work Programme. Credit: Kirsten Loewenthal

The European Science Foundation's Colette Schrodi presented the GenderSAFE project during the Diversity in Graphene session at Graphene Week. Credit: Giò Tarantini/ Gruppo Tonello

Students make graphene at IGE-Day held at Chalmers Industriteknik. Credit: Kirsten Loewenthal

Graphene Week brings the Graphene Flagship community together to learn (above), discuss the latests breakthroughs in 2D materials research and innovation (middle) and to celebrate results (below).
Credit: Giò Tarantini/ Gruppo Tonello

2D-PRINTABLE

Developing New 2D Materials and Heterostructures for Printed Digital Devices using sustainable liquid exfoliation and deposition methods

> 2D-PRINTABLE will be pivotal in allowing us to use liquid exfoliation methods to develop a palette of new 2D materials perfectly designed for use in high performance printed electronic applications."

Jonathan Coleman
Project Coordinator
Trinity College Dublin

TWO-DIMENSIONAL (2D) MATERIALS have reshaped materials science and nanotechnology by exhibiting exceptional physical and chemical characteristics that underpin emerging applications in areas such as optoelectronics, energy storage, sensing and advanced composites. Despite this promise, their widespread technological adoption remains limited by the lack of scalable and economically viable strategies to translate nanoscale properties into macroscopic systems. Overcoming this gap between the outstanding performance of individual nanosheets and practical large-area devices is therefore essential. The 2D-PRINTABLE project tackles this challenge through the use of sustainable, low-cost liquid exfoliation approaches. By combining state-of-the-art theoretical modelling with materials synthesis and environmentally friendly liquid exfoliation methods, the project enables the efficient production of a broad range of 2D materials, including conductive, semiconducting and insulating nanosheets. In parallel, it advances printing and liquid-phase deposition techniques to construct ordered multilayers and layer-by-layer heterostructures based entirely on 2D materials. These printed architectures are tailored for digital applications, unlocking new functionalities and performance levels. A central outcome of the project is the realisation of fully printed, all-nanosheet heterostructure light-emitting diodes (LEDs) as demonstrator devices. Through these efforts, 2D-PRINTABLE seeks to position 2D materials as a foundational platform for printed electronics and to enable the next generation of digital technologies.

PROGRESS IN 2025

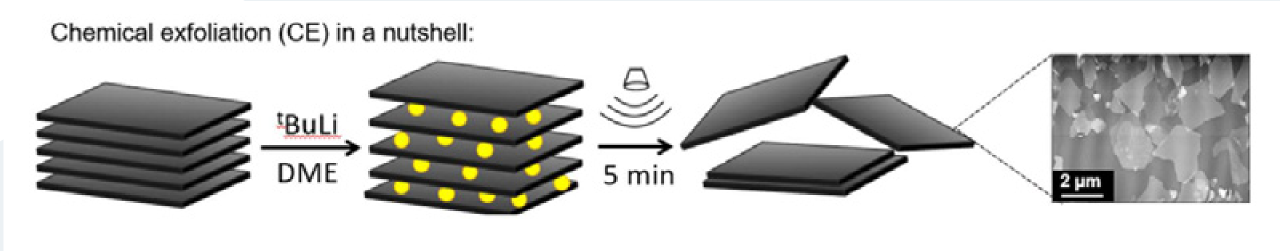
The most significant highlights and achievements of the 2D-PRINTABLE project include the following aspects:

Design and synthesis of a range of novel 2D materials using exfoliation in liquid media
Our approach to materials design relies on computer-based screening of known layered compounds from well-established crystal structure repositories, followed by large-scale computer simulations in order to identify materials that are easily exfoliable. In this way we created a comprehensive database available through the Materials Cloud Two-Dimensional Crystals Database, which currently contains close to 2,000 2D materials that can be derived from known inorganic compounds. This resource provides a strong foundation for discovering and developing new 2D materials with potential applications across many scientific and technological fields.

Guided by our computational screening results and application-driven considerations, we have synthesised more than 100 layered crystalline materials. These range from well-known benchmark materials such as MoS_2 and WSe_2, to less common and emerging materials like TlSe and Bi_2O_2Se. These, in-house synthesised materials, along with a smaller number of commercially sourced crystals, serve as the starting materials for producing 2D nanosheets through liquid exfoliation methods. From the wide range of 2D materials identified and produced during the early stages of the project, we have focused on those with the greatest technological relevance, while also considering the availability and sustainability of the constituent elements.

Using liquid-phase exfoliation with ultrasonication, we have successfully produced high quality nanosheets from several classes of materials, including transition-metal oxyhalides, binary and ternary chalcogenides, as well as other layered and non-layered compounds. In some cases, surface modification to improve the stability of the nanosheets in liquids was combined with exfoliation in a single processing step. We have also explored the use of high-shear mixing, which can produce larger quantities of nanosheets in shorter processing times, with mixed results depending on the material. Additionally, transition from lab to industrial scale production for selected novel 2D materials has been demonstrated by using BeDimensional proprietary wet jet milling technology, which enables production capacity of high quality 2D materials of ≥1 tonne/year.

For specific device fabrication, methods such as chemical and electrochemical exfoliation continue to be developed in order to produce high quality nanosheets exhibiting very large aspect ratio not achievable by ultrasonication alone. Both methods are relying on insertion/intercalation of different ions or molecules into the structure of starting bulk material, with or without the application of an external electric field, which once intercalated, readily delaminates upon brief ultrasonication yielding thin sheets of very large lateral dimensions. This process is illustrated in the accompanying figure and has enabled production of high quality nanosheets from novel 2D materials such as BiOCl, CrSBr, $MoWSe_2$ alloys, or $HfSe_3$, to name a few.



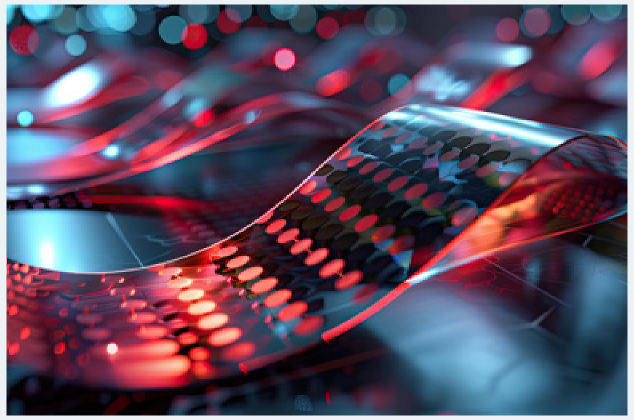
A schematic illustration of basic principles of chemical exfoliation.
Credit: BeDimensional S.p.A.

Chemical modification of nanosheets
In the past months, we explored novel chemical functionalisation strategies for two distinct classes of materials: layered compounds (CrSBr, $Bi_2Se_2O_5$, VOCl and PrOCl) and metal diborides (MgB_2, ZrB_2 and CrB_2). For the layered materials we focused on non-covalent functionalisation using a range of surfactants. Non-covalent functionalisation enables the modification of material surfaces without altering their intrinsic structure, allowing for the tuning of properties such as optical characteristics through dielectric interactions. Additionally, this approach provided insights into the colloidal stability of these materials in various solvents, an aspect that has not been thoroughly studied for these compounds. This opens new opportunities for developing stable dispersions of these materials.

For metal diborides (MgB_2, ZrB_2, and CrB_2), we investigated oxidation pathways and the impact of oxygen exposure on their properties. These materials are known for their excellent conductivity and high temperature stability, but oxidation can lead to undesirable degradation of their performance. We identified the oxidation processes and developed strategies to prevent these transformations through controlled inert processing techniques. By understanding how these materials interact with oxygen, we can design more stable and durable metal diboride-based materials for applications that require resistance to environmental degradation, such as in high-performance electronics and coatings. In both cases, we also developed optimised synthesis and processing techniques to fabricate these materials with high purity and controlled morphology, ensuring reproducibility and stability. This comprehensive approach of combining functionalisation strategies with advanced material fabrication lays the foundation for future applications, enhancing the properties of both layered materials and metal diborides. Our findings highlight the distinct advantages of non-covalent functionalisation for layered materials and oxidation resistance strategies for metal diborides. By leveraging these techniques, we provide valuable pathways for enhancing material properties and performance in a range of cutting-edge technologies.

Besides, substantial advancements have been made in the controlled formation of discrete assemblies of 2D materials using bidentate molecular linkers. The stepwise microfluidic assembly strategy has been optimised, refining the cyclic and sequential deposition of MoS_2, π-conjugated dithiolated molecules and WS_2. This has enabled more precise control over selective bridging at sulfur vacancies, ensuring reproducible fabrication of discrete heterostructures with well-defined size and morphology.

The multiscale characterisation protocol has been enhanced, integrating high-resolution SEM, *in situ* electrochemical impedance spectroscopy, Raman spectroscopy, and X-ray photoelectron spectroscopy. This comprehensive analysis has provided deeper insight into the growth mechanism, confirming selective edge bridging and verifying the structural integrity and compositional fidelity of the heterostructures. Additionally, initial experiments with other 2D transition metal dichalcogenides (TMDs) and variations of molecular linkers have demonstrated the potential for modular design, paving the way for more complex, functional heterostructures.



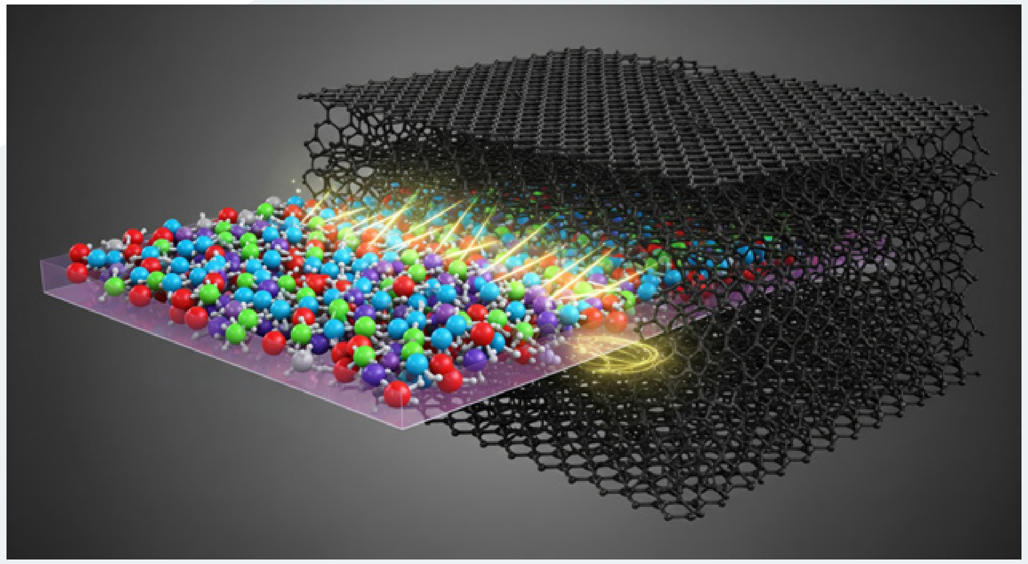
A depiction of an ultra-thin flexible nanoelectronic device.
Credit: Generated with AI

These developments provide a robust foundation for the controlled assembly of 2D materials as they bring the project closer to realising printable, low-dimensional functional architectures that go beyond the current state-of-the-art.

Printing and deposition of networks and heterostructures with controlled interfaces
Significant effort has been devoted to the liquid exfoliation of 2D materials, their formulation into inks and the printing of these inks to produce functional films, with particular focus on enhancing material quality and performance through optimised preparation methods.

A central achievement has been the production of novel 2D materials via liquid exfoliation. We have successfully exfoliated a broad range of 2D materials, including conductive electrochemically exfoliated graphene, semiconducting transition metal dichalcogenides and dielectric oxyhalides, providing access to the essential building blocks for electronic applications. A key aspect of this work has been the development of methods to produce nanosheets with very high aspect ratios suspended in liquids. These suspensions were subsequently formulated into inks, with careful adjustment of parameters such as viscosity and solvent composition to ensure compatibility with various printing and coating techniques.

Moreover, during the fabrication of solution-processed 2D vertical heterostacks, we identified pinhole formation and re-dispersion as the main challenges. To address these, multiple solution-processing approaches – including dip coating, spin coating and spray coating – were employed. High aspect-ratio insulating or semiconducting nanosheets were used to form compact, pore-free active layers. Multi-layer deposition with short intermediate annealing steps was



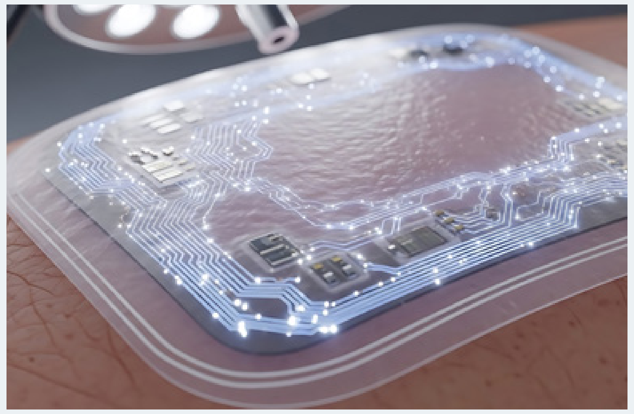
Visual representation of 3D heterostructure.
Credit: Generated with AI

introduced to densify the films and remove residual solvents, effectively minimising pinhole formation. In addition, high aspect-ratio metallic nanosheets, such as graphene or silver, were employed to bridge residual pinholes and establish intimate electrical contact with underlying layers. In some cases, zero-dimensional nanoparticles were incorporated to form a dense capping layer, further preventing pinholes from creating conductive paths. Re-dispersion issues were mitigated through careful selection of orthogonal solvents for each material in the heterostack.

Overall, these efforts have established robust fabrication protocols for 2D vertical heterostacks. The developed strategies are versatile and are expected to be extendable to a wide range of material combinations and device architectures, providing a strong foundation for future exploration in solution-processed 2D electronics.

Characterisation of nanosheets, networks and heterostructures
The exfoliation and utilisation of novel 2D materials derived from previously unexplored or underexplored bulk materials represent a core contribution to the main objective of 2D-PRINTABLE. This objective is to employ sustainable liquid-exfoliation techniques to develop a broad spectrum of new 2D materials, alongside the establishment of printing and liquid-deposition methods necessary to fabricate networks and multicomponent heterostructures with unprecedented properties, ultimately enabling next-generation printed electronic devices. Ideally, the exploration of new materials is guided by theoretical predictions of their properties, followed by the synthesis of the corresponding bulk layered materials in sufficient quantities. These aspects are documented in Deliverables D1.1 ("Database on available materials"), D1.2 ("Theory-identified novel 2D materials") and D1.3 ("Synthesis of bulk materials"), which collectively demonstrate significant progress achieved within the project timeframe. All these deliverables are publicly accessible on the 2D-PRINTABLE website.

Once the bulk materials are available, they are typically subjected to sonication-based liquid-phase exfoliation (LPE). This well-established method provides valuable information on exfoliation efficiency, nanosheet morphology and colloidal stability. Unlike electrochemical exfoliation, LPE is broadly applicable to insulators, semiconductors and metals alike. Materials that remain intact after exfoliation and exhibit good environmental and colloidal stability are then considered for



Visualisation of wearable medical sensor patch on human skin.
Credit: Generated with AI

subsequent electrochemical exfoliation to produce high aspect-ratio nanosheets, which are often critical for device performance.

We have recently reported progress in exfoliating layered materials that have not been previously studied via LPE, such as metal diborides, TaS_2, Bi_2SeO_5, CrSBr and $Na_2Cu_2TeO_6$.

Proof-of-concept digital devices based on printed networks and heterostructure
The field of printed electronics is rapidly advancing, driven by solution-processing methods that enable the fabrication of a wide variety of electronic components. Although printed devices typically do not yet match the performance of conventional silicon-based electronics, they offer distinct advantages, including lower production costs, mechanical flexibility, and compatibility with large-area deposition techniques. These attributes make printed electronics particularly attractive for emerging applications such as wearable devices, healthcare monitoring systems and electronic skins.

Among solution-processable materials, 2D materials have emerged as especially promising due to their exceptional intrinsic electrical, optical and mechanical properties. The 2D material family is extensive, comprising thousands of members with diverse functionalities, including conductive materials such as graphene, semiconductors like 2H-phase molybdenum disulfide (MoS_2) and insulating materials such as hexagonal boron nitride (hBN). Inks formulated from these materials can

2D-PRINTABLE booth at Graphene Week.
Credit: Uniresearch

Exhibition booth of our partner BeDimensional at Graphene Week.
Credit: Uniresearch

be applied in a range of printed devices, including transistors, solar cells, photodetectors and light-emitting diodes. To fully exploit the potential of 2D materials, it is essential to optimise solution-deposition methods to create uniform, high quality networks over large areas. Such networks must display properties suitable for device integration, including high charge-carrier mobility and conductivity.

A major challenge in printing inks composed of nanosheets with low aspect ratios (typically below 50) is that the resulting networks tend to be porous and disordered. In these networks, the junctions between nanosheets often form point-like contacts, which introduce high junction resistance and limit electrical performance. In this context, we have developed high quality networks of a wide range of 2D materials, which have been successfully integrated into flexible thin-film transistors (TFTs) exhibiting performance beyond the current state-of-the-art for solution-processed devices.

DISSEMINATION AND EXPLOITATION

The communication, dissemination and exploitation activities of the 2D-PRINTABLE project are designed to maximise the impact of its results and effectively engage with a diverse audience. These efforts target experts in nanomaterials, researchers, students, government bodies, industry leaders, suppliers, end-users and the general public, ensuring the broadest possible dissemination and utility of the project's outcomes. The central hub for project information is the 2D-PRINTABLE website (available at https://2d-printable.eu), which provides updates on key results, publications, partner events, and interviews with project partners. Additionally, updates are shared through the Graphene Flagship website under the cluster *"2D Materials of Tomorrow"*.

As part of its outreach, 2D-PRINTABLE publishes a bi-annual newsletter, highlighting recent achievements, partner activities and upcoming events, ensuring stakeholders stay informed. 2D-PRINTABLE also maintains an active presence on LinkedIn, where regular updates and announcements are shared to engage with the professional community.

The project has made impressive strides, with nearly 50 papers published on 2D-PRINTABLE, highlighting our dedication to pushing the boundaries of the field. A full list of the publications is available on the project website.

> By integrating 2D materials into critical technologies, the Advanced Materials Act can accelerate innovation, strengthen Europe's resilience and drive the twin green and digital transitions.

The 2D-PRINTABLE team has gained global recognition, with our research being featured at prominent events around the world. In 2025, we actively participated in high-profile gatherings such as Graphene Week 2025, Graphene 2025, the 9th EU-Korea Workshop and E-MRS Spring Meeting, FISMAT 2025, 2D TMDs 2025, NanoteC25, Flatlands Beyond Graphene and many others. Besides, 2D-PRINTABLE partners were involved in various educational activities such as MINT Days, Girls' Day and TYPE *(Transition Year Physics Experience)*. Through these coordinated efforts, 2D-PRINTABLE continues to establish itself as a key contributor to the development and application of nanomaterials, fostering collaboration and innovation across various sectors.

POWERED BY THE GRAPHENE FLAGSHIP

Working within the Graphene Flagship ecosystem has been a major asset for the 2D-PRINTABLE project, providing access to a broad network of academic and industrial partners. This collaboration has opened valuable opportunities for research partnerships, knowledge sharing and joint innovation. By connecting us with leading experts in graphene and other 2D materials, the Graphene Flagship has brought unique insights and synergies that help accelerate our work.

The Graphene Flagship has also played a key role in increasing the visibility and impact of 2D-PRINTABLE. Through initiatives such as Graphene Week, as well as its website, newsletter and LinkedIn, the Graphene Flagship has helped us connect with researchers, SMEs and industry leaders, raising awareness of our activities. These efforts are crucial for translating our research into real-world applications, driving progress in areas like electronics, energy and healthcare.

GRAPHENE FLAGSHIP ANNUAL REPORT 2025

2D-PRINTABLE co-hosted Graphene Week 2025 with Francesco Bonaccorso, Chief Scientific Officer at project partner BeDimensional, acting as Industry Ambassador for the conference. Credit: Giò Tarantini/ Gruppo Tonello

2D Materials of Tomorrow

PROJECT COORDINATOR
Jonathan Coleman, Trinity College Dublin, Ireland

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Technical University of Dresden, Germany
University of Chemistry and Technology Prague, Czech Republic
Uniresearch B.V., The Netherlands
Bundeswehr University Munich, Germany
Swiss Federal Institute of Technology in Lausanne, Switzerland

ASSOCIATED MEMBER
Sixonia Tech GmbH

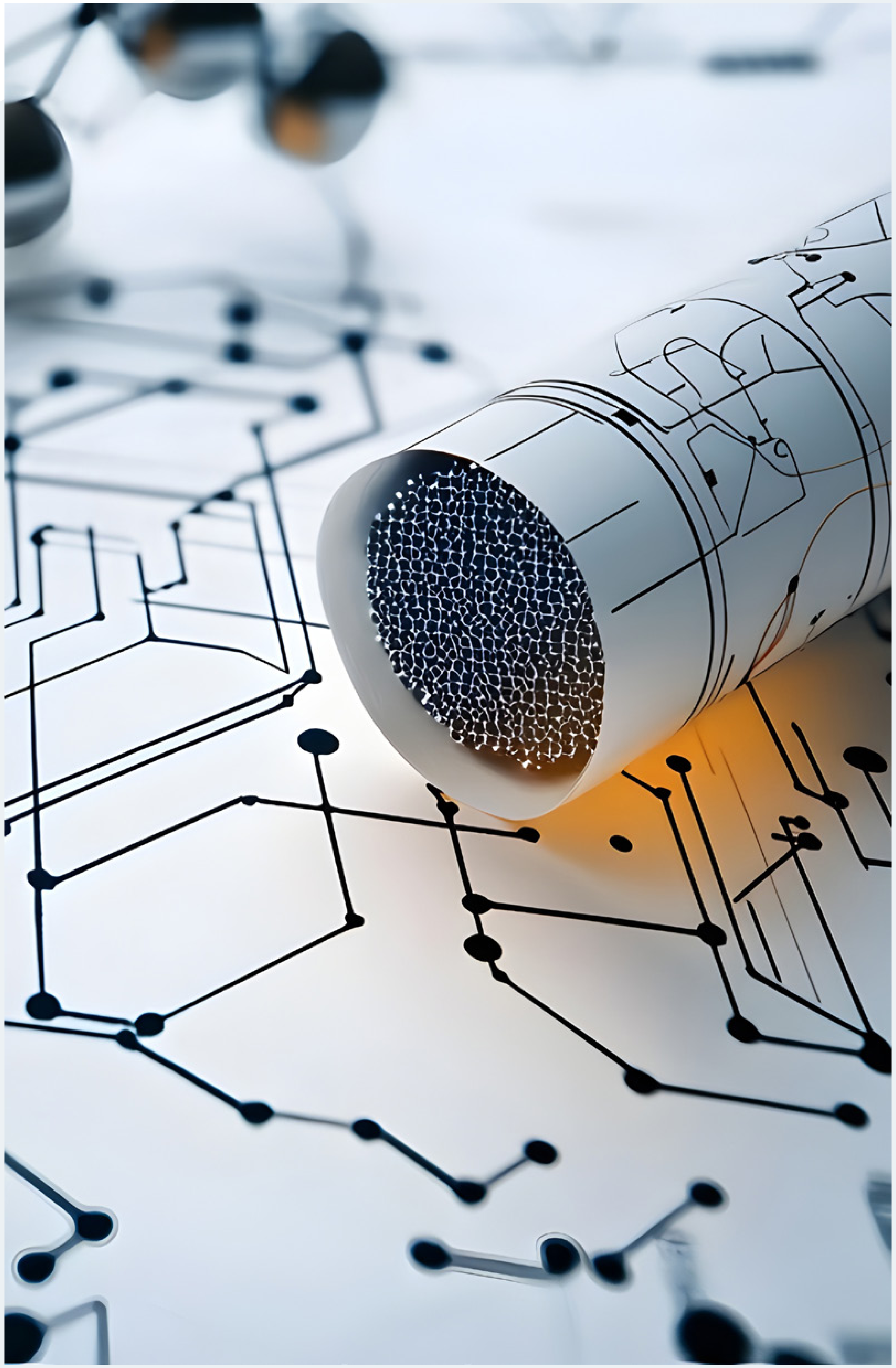
ON THE HORIZON
2D-PRINTABLE will continue its research through three main phases. The first phase focuses on designing and synthesising novel 2D materials using computational screening and literature analysis. In the second phase, the project will develop methods for printing or solution-depositing high-mobility nanosheet networks, with an emphasis on characterising the resulting structures. The third phase is dedicated to fully assessing the electrical properties of individual flakes, networks, films and heterostructures, while optimising the performance of printed structures and devices.

Efforts will prioritise refining exfoliation techniques, particularly sonication-assisted exfoliation of dielectric oxyhalides such as LaOBr, to reduce flake polydispersity and achieve thinner, more uniform nanosheets. The incorporation of additives to improve the mechanical stability and durability of films will also be explored, especially for demanding applications. Expanding solvent systems, with a focus on environmentally friendly options, will enhance exfoliation efficiency and allow fine-tuning of film properties for new materials like oxyhalides. Scaling up deposition techniques, particularly Langmuir-Schaefer deposition, toward industrial levels will ensure compatibility with large-scale production processes.

Application-specific testing will be expanded to evaluate material performance in printed electronics, sensors and energy devices. The database of exfoliable materials will be updated, and the understanding of their optoelectronic and mechanical properties further refined, strengthening the link between fundamental research and industrial application. During the demonstration phase, the project will showcase the potential of 2D materials in devices such as thin-film transistors, solar cells and LEDs.

Future work will focus on optimising production methods for selected materials based on application requirements and supplying them to partners for functionalisation, printing and device fabrication. Chemical and electrochemical exfoliation methods for producing high aspect-ratio nanosheets tailored to different device components will continue to be refined. For a few selected 2D materials, production upscaling will be optimised to industrial standards, considering solvent effectiveness, safety in large volumes, solvent exchange to produce ready-to-use dispersions and solvent removal to obtain pristine nanosheet powders.

These activities position 2D-PRINTABLE to advance scalable 2D material production, enabling next-generation printed electronics and innovative technologies.



GRAPHENE FLAGSHIP ANNUAL REPORT 2025

2D ENGINE

Engineering of ultimately thin, inherently 2D, semiconductors and insulators for the scaling of integrated digital (opto) electronic devices

SCALABLE THIN FILM growth of electronic-grade two-dimensional (2D) materials for nano- and opto-electronics is often limited by the availability of suitable engineered substrates. With very few exceptions, traditional large-area thin film growth techniques, such as CVD, MOCVD, ALD and MBE on solid, rigid sub-strates, yield 2D materials with inferior quality compared to small, micron-sized flakes exfoliated from bulk crystals. More specifically, thin film growth yields small crystalline domains, typically a few tens of nanometres, often slightly misoriented in-plane, resulting in fragmented discontin-uous films with low carrier mobilities. To overcome the shortcomings of conventional growth methods, in 2D ENGINE we employ a radically different technique, namely liquid metal catalyst (LMCat) growth of 2D materials which is a paradigm shift offering enhanced surface kinetics due to viscous flows that are absent in the case of growth on rigid solid substrates. First applied to the large-area growth of graphene on liquid copper with a significant contribution from some of the 2D ENGINE members, it was later extended to the growth of more complex 2D materials. In 2D ENGINE we employ this method for the growth of ultrathin hGaN, hBN and thin SiC films predicted to adopt a 2D structure at small thickness. We show their great potential to realise ultrathin transferable films of these important semiconductors and dielectrics with prospective applications in electronic and photonic integrated circuits.

> Leveraging the fertile environment within the consortium, already established during the first year, the members strengthened their collaboration in the second year, intensifying the joint work based on synchrotron facilities with the aim to validate the 2D phase of the grown materials using state-of-the-art infrastructure and expertise. The consortium has also made a decisive step forward to device fabrication by successfully transferring thin films of the new materials on prepatterned substrates to validate their electrical quality. This sets up the scene for the next year, creating prospects for fully functional optoelectronic devices.”

Athanasios Dimoulas
Project Coordinator
National Centre for Scientific Research DEMOKRITOS

HIGHLIGHTS FROM 2025

The main objective for the second project year was to deepen research on the most promising 2D candidates with the aim to prove their unique physical properties and obtain uniform films on a large scale. Moreover, we developed layer transfer methodology on a variety of target substrates, including prepatterned substrates, with the aim of obtaining functional electronic devices. 2D ENGINE made significant progress in all materials classes (semiconductors and insulators) and processes.

Predictions of the critical thickness at different temperatures by atomistic simulations
At the Fritz Haber Institute, we trained computationally efficient, yet accurate machine-learned interatomic potentials (MLIPs) against carefully benchmarked density functional theory (DFT) calculations to evaluate the thermodynamic stability at finite temperatures of the target materials which naturally occur in the wurtzite phase, namely SiC, AlN and GaN. While earlier zero-temperature estimates placed the critical thickness for preserving a hexagonal (2D) rather than wurtzite-like structure between roughly 5 and 20 layers, our finite-temperature simulations reveal a substantially reduced stability window. Molecular dynamics shows that the hexagonal phase becomes unstable already at 3–5 layers for the target materials, highlighting the stringent thermodynamic conditions under which truly planar 2D phases can be realised.

Our simulations offer further assistance in identifying these elusive few-layer phases. While we find that thermal broadening makes X-ray diffraction unreliable for distinguishing wurtzite-like from hexagonal structures at finite temperatures, Raman spectroscopy provides sharp and robust fingerprints that not only differentiate the two phases but also resolve stacking sequences, delivering a practical and dependable tool for phase identification during growth.

Encouragingly, our simulations further show that hexagonal layers can remain locally stabilised in predominant wurtzite stacks. This finding opens new opportunities for deliberately synthesising mixed-phase heterostructures with tunable electronic properties, rather than relying solely on the stab-ilisation of a uniform structural phase.

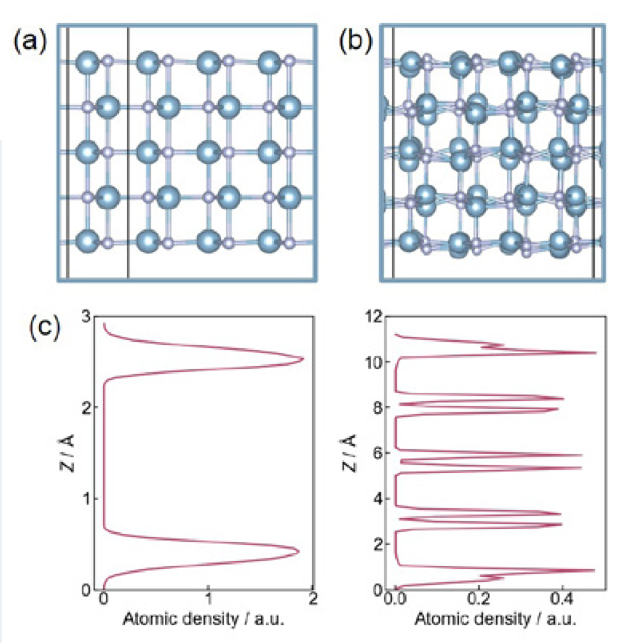


Figure 1. (a) DFT optimised h-AlN 5ML structure at 0K. (b) AlN 5ML structure during MLIP-MD simulation at 300K. (c) Laterally averaged atomic density distribution for AlN 2ML (left) and 5ML (right) at 300K. The 2ML structure exhibits hexagonal-like planar layers, while the 5ML structure exhibits wurtzite-like buckled layers.

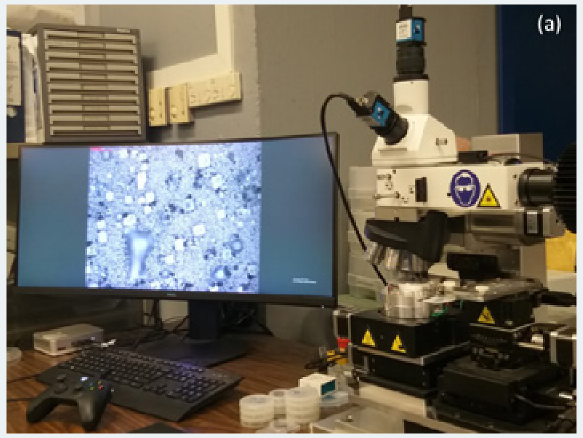
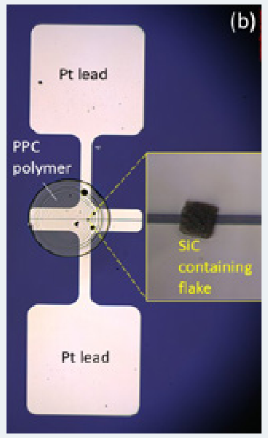


Figure 2. (a) automatic, fully motor-ised transfer stage for layer transfer and precise positioning. (b) SiC containing flake transferred and positioned with precision onto prepatterned substrate with Pt leads for electrical validation. The PPC layer is part of the transfer process. It is removed by heating before electrical measurements.



Production of transferable (suspended) inhomogeneous SiC films
Using LMCat, inhomogeneous SiC films can be obtained which consist of bulk SiC crystals firmly attached to a SiC-containing surface layer over the entire cm-scale substrate. After removal of Cu by wet etching, the loosely attached inhomogeneous film is detached from the growth Si substrate by dry, mechanical methods and placed on a variety of clean target substrates (SiO_2/Si, sapphire, prepatterned substrates, etc.). The transferred layers end up in flakes with sizes in the range of 10–100 μm. We show that by reducing the temperature and time of growth it is possible to minimise the size and number of crystals or eliminate them in favour of the surface SiC-containing layer, which results in more homogeneous, thinner films. The morphological characteristics (shape, size) of the SiC areas depend on the thickness of the Cu layer.

The resistivity of the films transferred on prepatterned substrates is estimated in the range of 25–250 Ω-cm which is compatible with semiconductor resistivity and is within the range of reported resistivities for SiC depending on the purity and growth methodology. The fully motorised layer transfer stage (Figure 2(a)) charged to 2D ENGINE and installed at National Centre for Scientific Research DEMOKRITOS (NCSRD) is a key enabler since it provides the necessary tools for transfer and precision positioning of our SiC-containing flakes (Figure 2(b)) and assists the realisation on photonic and electronic devices targeted in this project.

AMO and the NCSRD are closely collaborating to develop the necessary protocols for sample exchange, polymer removal and optimisation of the test patterns in order to improve the electrical measurements and identify the field effect transistor layout that is optimal for the SiC device characterisation.

Large area growth of hBN with good coverage
Experiments of hBN growth were conducted using both the LMCat reactors (University of Patras, European Synchrotron Radiation Facility (ESRF)) and DirectSepa reactors (Leiden Probe Microscopy). The DirectSepa reactor faced challenges with precursor gas delivery, which caused concentration gradients and inconsistent growth across the sample. While some regions formed thick (~100 nm) hexagonal structures, they lacked overall uniformity. In contrast, the LMCat reactors provided much better control over the growth process. Supported by real-time ROM tracking and *ex-situ* analysis (Raman, XPS, and AFM), the LMCat system produced high-purity, stoichiometric hBN. These layers were found to be uniform and thin, with significantly fewer defects and less strain than those produced by the DirectSepa reactor.

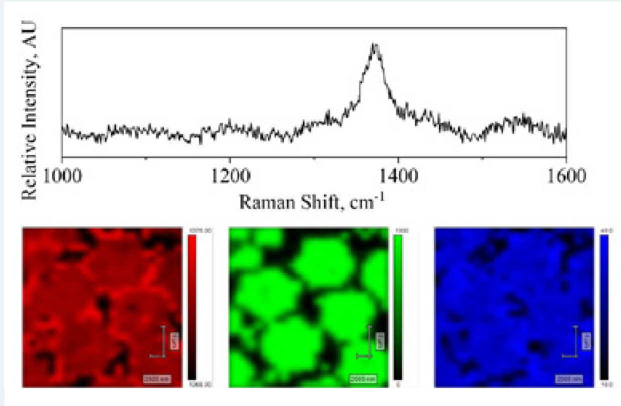


Figure 3. Indicative results from Raman characterisation for the hBN growth experiments.

Figure 4. 2DMIT workshop participants.
Credit: 2D ENGINE

Effect of N precursor and liquid metal choices on the morphological characteristics of GaN

At Leiden University/Leiden Probe Microscopy and the ESRF we have grown GaN 2D films on liquid Ga and GaCu alloys. During growth, we observe the films using optical microscopy and synchrotron X-ray-based techniques such as GID and XRR, and *ex-situ* characterisation using SEM/EDX, XPS, and Raman spectroscopy has been performed after growth. While in the experiments with Ga-rich (50 and 100 Ga at. %) alloys, the optical microscopy images showed scarce crystals coming in and out of the field of view of the microscope. Experiments conducted on Cu-rich alloys enabled us to observe the formation of a large, continuous thin film. While Ga-rich alloys yielded GID patterns that could be indexed as the 3D wurtzite phase, the GID patterns recorded on the crystals grown on Cu-rich liquid alloys typically exhibited Crystal Truncation Rods (CTRs), indicative of the presence of 2D crystals. These observations are in line with the results of Raman spectroscopy. The band observed in Raman spectroscopy for 2D GaN matches with the simulated Raman spectra calculated by the Fritz Haber Institute of the Max Planck Society. SEM/EDX confirmed the presence of Ga and N species in the films, and thin crystals were observed for films grown on Cu-rich GaCu alloys.

DISSEMINATION AND COMMUNICATION

2D ENGINE implemented most of the dissemination and communication plan in its first year. In brief, the coordinator constructed a website (https://www.2dengine.eu), AMO hosted a LinkedIn account on their platform, ESRF employees montaged a four minute video and finally 2D ENGINE supported three associated members. In the second year, the consortium continued the activities making effective use of dissemination and communication channels and they have prepared three manuscripts with joint work for submission early in 2026.

The most important dissemination event in the second year was the workshop “2D Materials and Interfaces of Tomorrow: Synthesis and Characterisation” organised by the 2D ENGINE partner ESRF in Grenoble on 10–11 December 2025. The workshop featured 28 oral presentations and a poster session with 18 posters, and brought together over 60 participants from ~16 institutions, spanning ESRF and French laboratories (including ILL, CEA Spintec/Leti/LNHB-MA, CNRS Institut Néel/Université de Lyon/INSA, SOLEIL, University of Picardie), as well as European partners and external users (2D-PRINTABLE partners from Kassel University, DESY, Politecnico di Milano, Philipps-University Marburg, FTMC Vilnius, Koç University). Beyond showcasing recent advances in 2D synthesis and interface science, the event stimulated follow-up collaborations and seeded concrete ideas for coordinated experiments and future beamtime proposals at ESRF.

POWERED BY THE GRAPHENE FLAGSHIP

2D ENGINE is complementary to most of the projects in the Graphene Flagship, giving little margin for joint activities. Despite this, synergies have been built in the second year, including:

- The recent workshop organised in Grenoble by ESRF, a member of 2D ENGINE, brought together 2D ENGINE with 2D PRINTABLE and associated member CEA, as well as other researchers from institutions in the Grenoble area.
- Taking advantage of the fertile environment for networking established by the Graphene Flagship, 2D SPINTECH partner Chalmers University of Technology and 2D ENGINE partner NCSRD set up a successful project, AMSwitch, to beat the fierce competition of 2% success rate of EIC Pathfinder Open framework program. The project, starting 1 March 2026, combines 2D materials with altermagnets aiming for new logic switches.
- Triggered and supported by the Graphene Flagship, members of 2D ENGINE, including the coordinator, actively participated in the newly formed IAM-I association on innovative advanced materials to shape the new SRIA of advanced materials and impact the European Union’s Advanced Materials Act initiative.

SAILING FORWARD

During the next period, the main target is to capitalise on the progress made so far and disseminate the results, increase the project visibility and secure a strong contribution to the Graphene Flagship community. Moreover, we aim to show that our materials, based on their performance in test devices, can be used to enhance the functionality and efficiency of electronic and photonic integrated circuits. In summary, our action plan for the next year is as follows:

- Publish our results on GaN, BN and SiC targeting high impact journals.
- Successfully transfer LMCat GaN and hBN films on prepatterned substrates for electrical validation.
- Fabricate twisted BN bilayers (parallel bilayers) and verify their ferroelectric properties, then combine with ultrathin oxides (Al_2O_3, SiO_2) to fabricate ferroelectric tunnel junctions operating as memristor devices for neuromorphic applications.
- Optimise our transistor and LED fabrication processes involving the GaN and SiC LMCat layers.
- Improve project visibility by issuing at least two newsletter illustrations in the 3rd project year period.
- Intensify our contribution to the Graphene Flagship community including the organisation of a workshop as an integral part of the upcoming Graphene Week 2026.

2D Materials of Tomorrow

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Athanasios Dimoulas, National Centre for Scientific Research DEMOKRITOS, Greece

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PARTNERING PROJECTS
MINERVA

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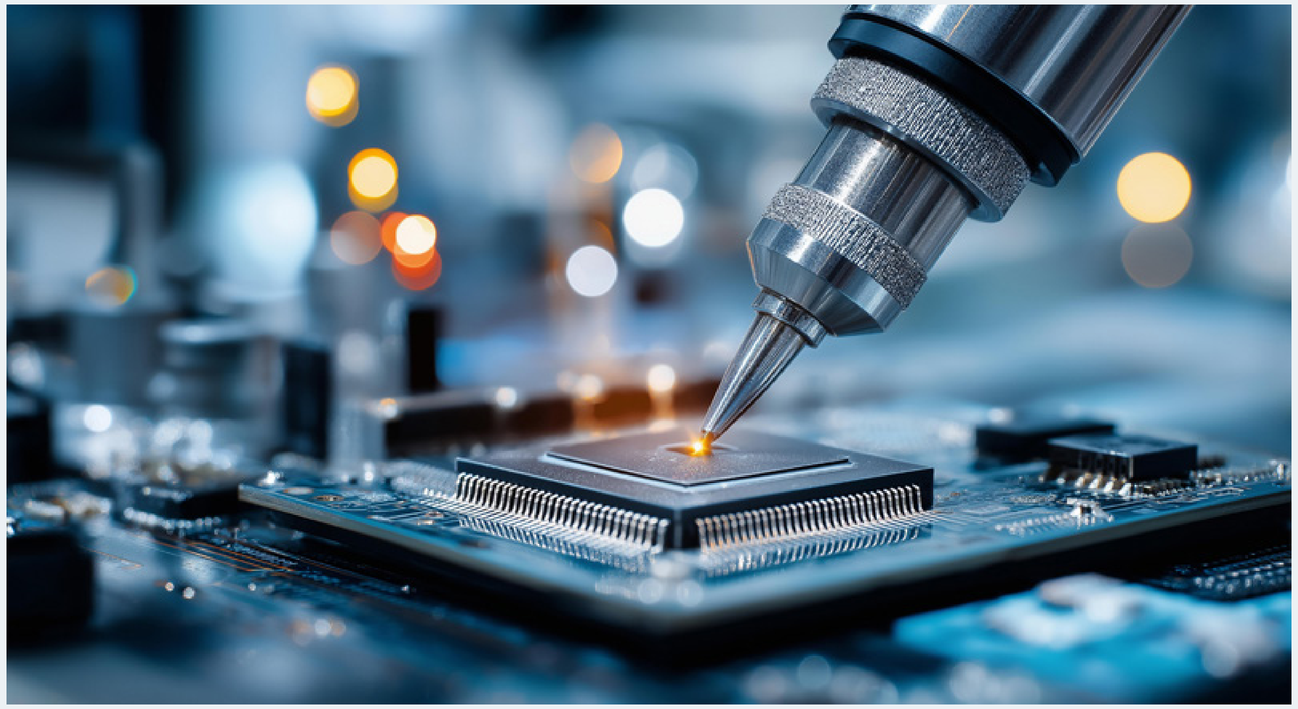
Uppsala University
Université Catholique de Louvain
Commissariat à l’Energie Atomique et aux Energies Alternatives (CEA)
Water2kW
International Iberian Nanotechnology Laboratory



2DSPIN-TECH

Spin-orbit torque (SOT)-driven spintronic devices based on 2D materials for next generation memory applications

THE EFFICIENCY of spin-orbit torque (SOT) memory applications has historically been constrained because traditional materials generate only an in-plane spin current. Critically, even recent low-symmetry materials have not produced sufficient out-of-plane spin current for practical use. 2DSPIN-TECH is addressing this by studying advanced two-dimensional (2D) materials, including topological Weyl semimetals and Janus semiconductors, known for generating large, current-induced out-of-plane spin polarisation. Initial device testing, combining these 2D materials with a magnetic layer, suggests the out-of-plane spin Hall conductivity could be an order of magnitude greater than previously reported values. Furthermore, 2DSPIN-TECH researchers are leveraging Graphene Flagship success to synthesise and investigate 2D ferromagnets (FMs) capable of operating beyond room temperature. This atomic-level control over magnetism is key to enabling new device architectures. These collective findings prove that 2D spin-orbit materials (SOMs) exhibiting giant spin-orbit coupling, alongside beyond-room-temperature 2D FMs, provide a highly promising foundation for developing energy-efficient, field-free and tunable SOT-based memory technologies (see Figure 1).

PROGRESS IN 2025

Growth of 2D TMDs and characterisation

The project established reproducible protocols for growth, transfer, and characterisation of single-crystal transition metal dichalcogenide (TMD) monolayers as two-dimensional spin-orbit materials (2DSOMs). To this end, high-quality Janus SeMoS and SeWS monolayers were synthesised on polycrystalline gold (Au) foils using the chemical vapour deposition (CVD) technique from solid precursors. Large, uniform single-crystal domains with lateral sizes ranging from 10 µm to 50 µm were reproducibly obtained. Raman fingerprints and angle-resolved X-ray photoelectron spectroscopy confirmed the asymmetric Se-Mo-S and Se-W-S atomic configurations. Owing to their intrinsically broken out-of-plane mirror symmetry, these monolayers provide a promising platform for spintronics. For device fabrication, the Janus monolayers were successfully transferred onto pre-marked chips while preserving their morphology and optical quality.

In addition, Janus monolayers were grown on Au(111) single crystals to investigate the nanoscale topography and electronic properties. Complementary characterisation using scanning tunnelling microscopy (STM), low-energy electron diffraction (LEED), and angle-resolved ultraviolet photoelectron spectroscopy (ARUPS) revealed the formation of Moiré pattern and spin-orbit splitting of approximately 170 meV at the K point of the valence band (see Figure 2).[1]

"2DSPIN-TECH has achieved remarkable breakthroughs this year – we have now demonstrated that two-dimensional materials can truly unlock the full potential of spintronics, delivering faster, more energy-efficient and magnetic field-free memory devices. Through our collaborative efforts in material synthesis and interface engineering, we've proven that van der Waals heterostructures can efficiently read and write information. Looking ahead, we're focusing on optimising device performance and deepening our understanding of magnetisation switching phenomena through advanced simulations and atomic-scale engineering – insights that will guide us toward the next generation of spintronic devices."

Prof. Saroj Dash
Project Coordinator
Quantum Device Physics Laboratory
Chalmers University of Technology

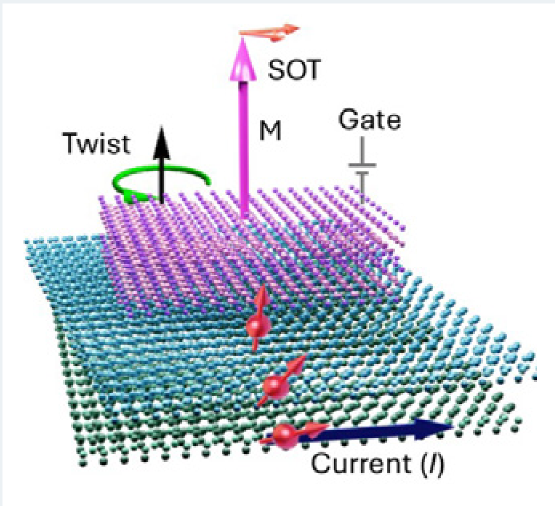


Figure 1. Schematics of the spin-orbit torque (SOT) memory device using all 2D materials heterostructures. A charge current in 2D spin-orbit material can generate out-of-plane spin polarisation for efficient switching of magnetisation in a 2D magnet. Furthermore, gate and twist angles between the layers can be used for controlling SOT efficiency.

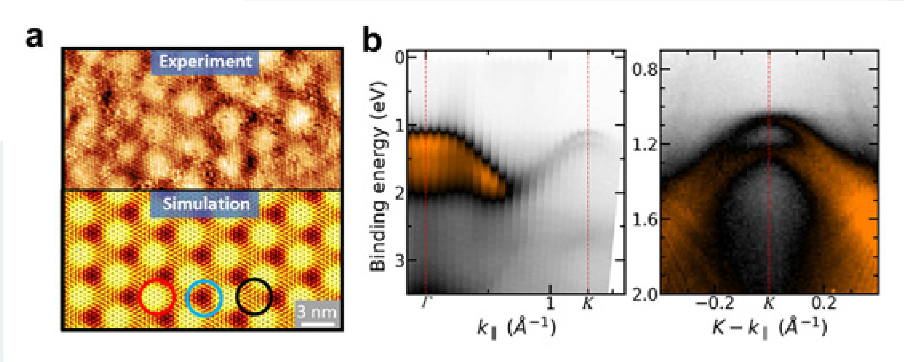


Figure 2. (a) STM (−1.1 V, 0.5 nA, 4.2 K) (top) and simulated STM images (bottom) of a Janus SeMoS on Au(111). ARUPS data (b) along the Γ–K direction and around the K point of Janus SeMoS on Au(111). Adapted from Ref.[1]

Spin signals at room temperature

The project has developed new ultra-thin magnetic materials that remain magnetically ordered well above room temperature, a key requirement for practical technologies. By carefully combining different elements, the researchers were able to tune how the magnetism is oriented and even create materials where two types of magnetism coexist within a single crystal – an unusual and valuable property. These materials were thoroughly characterised to understand how their magnetisation can be efficiently controlled using electrical currents rather than external magnetic fields. This work lays the foundation for future low-power memory and logic devices based on spin-orbit torque, which promise faster operation and reduced energy consumption compared to today's technologies.[2]

The team developed high-performance graphene-based devices in which graphene is fully encapsulated by an atomically smooth insulating material, hexagonal boron nitride (hBN). This approach dramatically improves the quality of graphene, allowing electrons – and their spin – to travel with very little scattering, a regime known as ballistic transport. Using advanced magnetic contacts, the researchers demonstrated efficient injection and detection of spin signals at room temperature. These results enable detailed studies of spin behaviour at the nanoscale and represent an important step toward ultra-low-power spin-based electronics that operate with minimal energy loss.[3]

In addition to flat structures, the project explored new device geometries based on curved and rolled graphene systems. These architectures enhance the interaction between electrical currents and spin signals, enabling stronger measurable responses than in conventional planar devices. Such designs make it possible to convert alternating electrical signals into steady spin-dependent outputs, a process known as spin rectification. These findings open new routes toward compact, efficient spintronic components that can generate large signals without requiring strong magnetic fields, further broadening the technological potential of graphene-based spintronics.[4]

Heterostructure of 2D materials for spin-orbit coupling

The consortium has made significant progress in controlling electron spin in two-dimensional (2D) materials for next-generation SOT devices based on ExSOtronic effects, where the spin of electrons is influenced simultaneously by spin-orbit coupling (SO) – the interaction between an electron's motion and its intrinsic spin – and magnetic exchange interactions (Ex), induced when graphene is placed next to a magnetic material. By combining these effects in carefully engineered heterostructures, we can achieve unprecedented control over electron spin, a key step toward faster and more energy-efficient electronic devices.

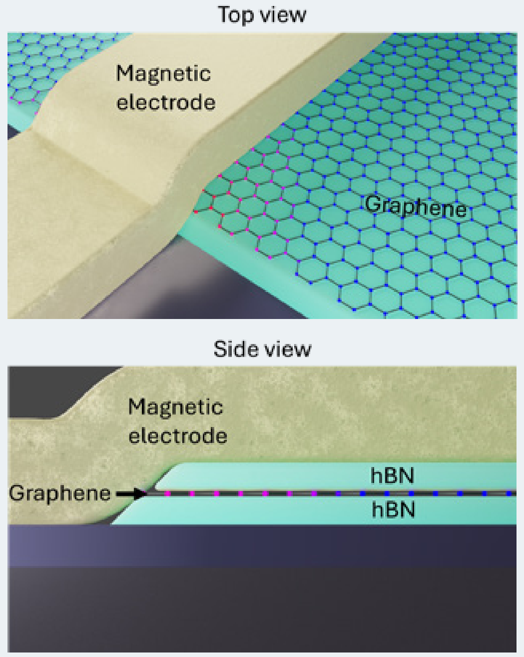


Figure 3. Tuneable spin-polarised Quantum Point Contacts to graphene.

Using advanced first-principles simulations, we studied trilayers composed of graphene sandwiched between spin-orbit materials (WS_2 or WSe_2) and ferromagnetic layers ($Cr_2Ge_2Te_6$). We found that small changes in the twist angle or lateral alignment between layers strongly affect spin polarisation in graphene, producing either ferromagnetic or antiferromagnetic states. In particular, a 30° twist between graphene and WSe_2 causes the out-of-plane spin-orbit coupling to vanish, which is expected to strongly impact spin-orbit torque mechanisms. We also developed an approach using spin parameters from bilayer substructures to predict the full heterostructure's Dirac band features, providing an effective roadmap for designing spintronic materials.

This theoretical work was complemented by experiments across partner institutions. In WSe_2/bilayer graphene devices, we induced and tuned spin-orbit coupling using displacement fields, extracting valley-Zeeman (Ising) of 1.6 meV and Rashba SOC of 11 meV, exceeding theoretical expectations. Applying pressure, we observed spin-orbit coupling enhanced by ~60%, showing how interlayer spacing can tune spin properties. In lateral spin-valve devices with bilayer graphene and hexagonal boron nitride, we demonstrated high-quality spin transport and tunable spin currents via magnetic exchange proximity. More complex heterostructures incorporating ferromagnetic CrSBr

GRAPHENE FLAGSHIP ANNUAL REPORT 2025

exhibited quantum Hall plateaus, de Haas-van Alphen oscillations, and split Landau levels, confirming the coexistence of spin-orbit and magnetic exchange effects. Together, our results highlight the potential of twist-angle, pressure, and gating control to engineer 2D heterostructures for advanced spintronic technologies.

Two-dimensional quantum material heterostructures can offer a promising platform for energy-efficient non-volatile spin-based technologies. However, energy-efficient magnetisation switching and spin dynamics experiments to understand the basic spin-orbit torque phenomena are so far lacking. Here, we demonstrate unconventional out-of-plane magnetisation dynamics, and energy-efficient and field-free spin-orbit torque switching in a van der Waals heterostructure comprising out-of-plane magnet Fe_3GaTe_2 and topological Weyl semimetal $TaIrTe_4$.[5] We measured non-linear second harmonic Hall signal in $TaIrTe_4$/Fe_3GaTe_2 devices to evaluate the magnetisation dynamics, which is characterised by large and tunable out-of-plane damping-like torque. Energy-efficient and deterministic field-free SOT magnetisation switching is achieved at room temperature with a very low current density. First-principles calculations unveil the origin of the unconventional charge-spin conversion phenomena, considering the crystal symmetry and electronic structure of $TaIrTe_4$. These results show that van der Waals heterostructures provide a promising route to energy-efficient, field-free and tunable spintronic devices.

DISSEMINATION AND EXPLOITATION

In the second year, 2DSPIN-TECH significantly amplified its outreach and communication efforts. We effectively leveraged our website and social media channels (LinkedIn and X), gaining over 800 followers and attracting more than 2,000 unique visits to the project website (https://graphene-flagship.eu/focus/2d-materials-of-tomorrow/2dspin-tech). The website features 15 updated articles detailing project news and key results. To engage a wider audience and inspire future generations, we launched a new series profiling young scientists, showcasing their motivations, commitment, passion for science and encouraging interest in 2D materials research. The project researchers generated substantial research output, with all achievements being published in high-quality, peer-reviewed journals or presented at major international conferences. Specifically, nine articles were published in peer-reviewed, open-access journals in 2025. Furthermore, the research was presented at 15 international conferences and workshops, including both oral presentations and poster contributions, ensuring broad scientific dissemination.

During the Graphene Week 2025 conference, 2DSPIN-TECH organised a successful workshop titled “2D Quantum and Spin Materials” featuring presentations by four top international scientists on advanced applications of graphene, TMDCs and 2D magnetic materials in quantum and spintronics. These presentations offered valuable insights into advanced spintronic studies and recent technical achievements, sparking the audience’s curiosity and leading to productive discussions and Q&A sessions.

2DSPIN-TECH’s exploitation strategy is focused on a technology-push approach, centred on networking, outreach, stakeholder engagement and market analysis. Through close collaboration with other Graphene Flagship projects, relevant stakeholders and external partners, project members have successfully submitted joint multi-partner proposals and applied advanced instruments to analyse developed materials and devices. Building on an initial market trend analysis, the

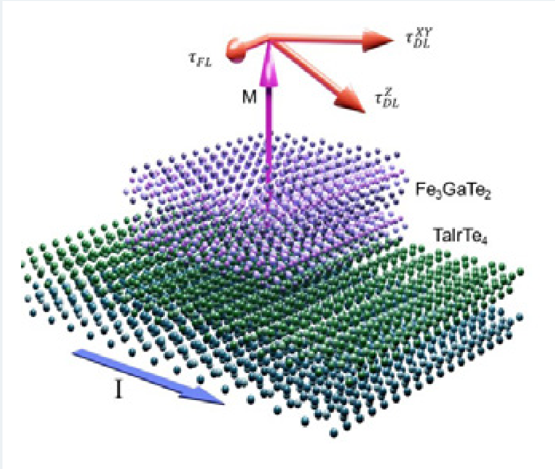


Figure 4. We demonstrate energy-efficient field-free spin-orbit torque (SOT) switching and tunable magnetisation dynamics in a van der Waals (vdW) heterostructure comprising out-of-plane magnet Fe_3GaTe_2 and topological Weyl semimetal $TaIrTe_4$.[5]

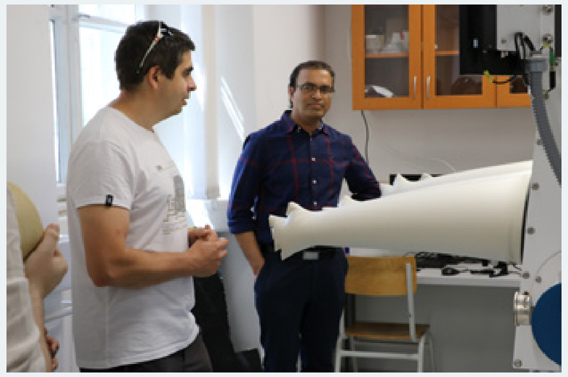


Figure 5. Peter Makk and Saroj Dash discussed in the lab. Credit: Jonas Löfvendahl

project is planning to invite key industrial stakeholders to participate in future roadmap discussions, ensuring market alignment.

POWERED BY THE GRAPHENE FLAGSHIP

The collaborative environment fostered by the Graphene Flagship has significantly enhanced our access to diverse expertise and resources across various working groups. The initiative’s Roadmapping Group guided our investigation into the potential market and future trends for MRAM. The Innovation Group provided a platform for sharing exploitation experiences and addressing challenges. Through the Standardisation Group, we gained the opportunity to contribute to existing standard projects and appreciate the importance of regulations for the volume production of 2D materials. Additionally, the Dissemination Working Group created avenues for collaboration and increased 2DSPIN-TECH awareness by sharing our content online. Furthermore, Graphene Week offered a crucial opportunity for our partners to present their latest research, engage in discussions with representatives from other Graphene Flagship projects, and gain insights from 2D materials experts beyond Europe.

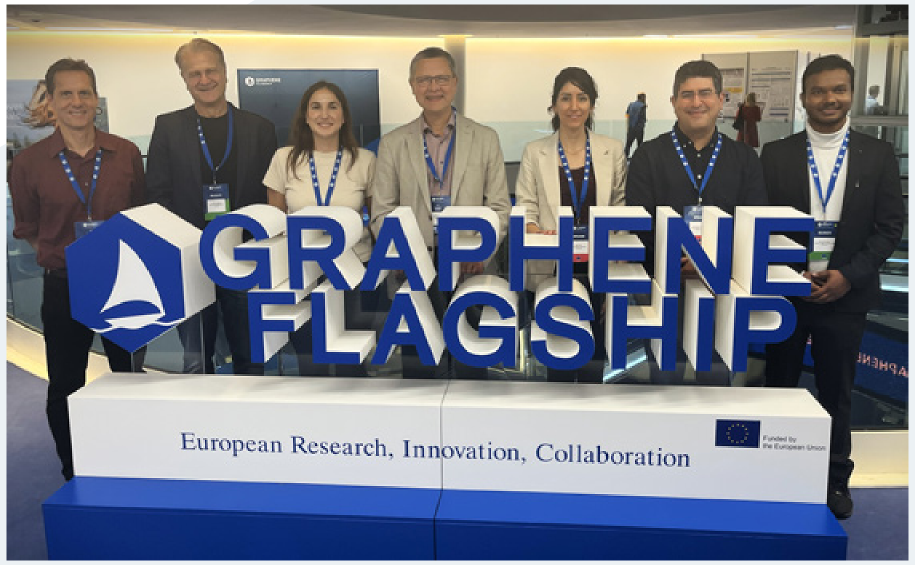


Figure 6. Graphene Week in Vicenza, Italy. Credit: Jonas Löfvendahl

SURPRISE ME

We discovered the coexistence of ferromagnetic and antiferromagnetic orders in 2D magnets $(Co_{0.5}Fe_{0.5})_{5-x}GeTe_2$ above room temperature, inducing an intrinsic exchange bias and canted perpendicular magnetism was discovered.[2] Such non-trivial intrinsic magnetic order enables us to realise energy-efficient, magnetic field-free and deterministic spin-orbit torque (SOT) switching.[2]

ON THE HORIZON

As we advance 2DSPIN-TECH toward more practical device implementation, our greatest challenges lie in reproducibly making these atomic-thin materials while maintaining the exceptional interface quality. We must overcome the complexity of integrating multiple 2D material systems into robust, manufacturable heterostructures, and we need to develop standardised protocols for tunability and reproducibility. Our strategy will focus on refining 2D material growth, heterostructure stacks through iterative device optimisation, utilising advanced computational modelling to predict and enhance performance and working toward demonstrating scalable fabrication pathways that can bridge the gap from laboratory prototypes to real-world applications. This journey demands innovation not just in physics and materials science, but in engineering rigor – and that’s precisely where our collaborative efforts will make the difference.

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2D Materials of Tomorrow

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PARTNERING PROJECTS
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MNEMOSYN

ASSOCIATED MEMBERS
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Uppsala University
Université Catholique de Louvain
Paul Drude Institute for Solid State Electronics, Leibniz-Institut im Forschungsverbund
SPINTEC
Max Planck Institute of Microstructure Physics
Ankara University
Centre Interdisciplinaire de Nanoscience de Marseille (CINaM), University of Marseille

2DSPIN-TECH

SAFARI

Safe and sustainable by design graphene-MXenes hybrids

SAFARI IS A HORIZON EUROPE PROJECT advancing sustainable and safe innovation in two-dimensional (2D) materials through the development of graphene-MXene hybrids. Building on graphene's established excellence, SAFARI combines the complementary properties of MXenes and graphene to enable applications such as biosensors, conductive inks and electromagnetic interference shielding. With a consortium of 11 partners from eight European countries, the project focuses on non-toxic, scalable synthesis routes, optimised material performance and safe-by-design approaches, reinforcing Europe's leadership in responsible 2D materials development. Beyond material innovation, SAFARI integrates safety, sustainability and performance considerations across the entire development chain, from precursor production to application validation. The project also emphasises digital modelling, life-cycle assessment and stakeholder engagement to guide responsible technology development and prepare pathways for industrial adoption. By aligning scientific excellence with environmental and societal responsibility, SAFARI contributes to establishing new European standards for the safe and sustainable deployment of next generation 2D material technologies.

> SAFARI is showing that the next generation of 2D materials can be both high-performing and responsibly developed. In 2025, the project has made strong progress in producing new graphene–MXene hybrid materials while improving how they are manufactured, tested and scaled."

Dariusz Garbiec
Project Coordinator
Poznanski Institute of Technology

PROGRESS IN 2025

Preparation of MAX phases
To enable reliable MXene production, SAFARI has optimised the synthesis of MAX phase precursor materials. Advanced sintering and milling techniques were refined to produce uniform, high-purity precursor powders while increasing batch sizes suitable for scale-up. Process modelling and simulation tools were used to design manufacturing setups that ensure consistent heating, stable processing conditions and reproducible material quality. In addition, optimisation of particle size and purity has improved the efficiency of subsequent MXene production. These developments establish a robust and scalable supply of precursor materials, providing an essential foundation for reproducible MXene manufacturing and future industrial deployment of graphene–MXene hybrid technologies. Ongoing work focuses on further improving energy efficiency of processing routes and evaluating equipment configurations suitable for pilot-scale production.

MXenes production
Within work package six, SAFARI has developed safer and more efficient routes for producing MXenes from MAX phase precursors. Alternative synthesis pathways were explored to reduce dependence on hazardous chemicals while maintaining material performance. A major technical achievement is the successful synthesis of Ti_3C_2 MXenes and Nb_4C_3 MXenes, a material class that has historically been extremely difficult to produce using conventional methods. By identifying new processing conditions and reaction pathways, SAFARI overcame long-standing limitations in MXene fabrication. These advances broaden the accessible library of MXene materials, improve production reliability and open new opportunities for applications in electronics, sensing and protective coatings.

Current efforts are directed toward improving process reproducibility and increasing production volumes while maintaining safety and material consistency.

Physicochemical characterisations of MXenes
SAFARI has carried out extensive physical and chemical characterisation of newly produced MAX phases and MXenes. A broad range of microscopy, spectroscopy and electrical measurements confirmed the layered structure, composition, surface chemistry and conductivity of the materials. These analyses verify that the safer synthesis routes deliver materials with properties suitable for real-world applications such as sensors, conductive coatings and electromagnetic interference shielding. In parallel, advanced computer simulations have been implemented to predict MXene properties before synthesis. These digital models guide experimental design, reduce trial-and-error testing and accelerate material development while lowering resource use and laboratory risks. Continued characterisation work supports quality control during scale-up and guides optimisation of hybrid graphene–MXene formulations.

Toxicological and eco-toxicological profile of MXenes
SAFARI has made significant progress in evaluating the safety of MXenes. Toxicological and environmental studies (*in vitro* and *in silico*) are being conducted to understand how these materials interact with biological systems and ecosystems throughout their life cycle. At the same time, production routes and material choices have been reviewed to minimise hazardous chemicals, energy consumption and waste generation. By combining safety testing with safe-by-design manufacturing strategies, SAFARI ensures that high-performance 2D materials are developed with a clear understanding of their potential health and environmental impacts, supporting responsible innovation and future regulatory readiness. Upcoming activities will focus on consolidating test results and feeding findings back into material and process design.

Sustainability, social acceptance and data integration
A key innovation of SAFARI is the integration of sustainability and safety assessments directly into material development.

Figure 1. Poster presentation at the Sustainable Printed Electronics Conference 2025.

Early-stage life cycle sustainability assessments have been applied to MAX phases and MXenes manufacturing steps to identify opportunities to reduce environmental impact and improve resource efficiency.

In parallel the SAFARI safe and sustainable by design (SSbD) decision-support-system is being developed to support end users gathering and structuring all relevant information and applying SSbD concepts in a holistic way when developing graphene-MXene-based materials and products. This online SAFARI tool is not developed from scratch but a special version of the ENICHMA tool which combines the existing frameworks and tools earlier developed in four EU-funded projects GUIDEnano, GRACIOUS, SAbyNA and SbD4nano.

Activities addressing social acceptance, transparency and data integration further support responsible innovation. Together, these efforts ensure that new graphene–MXene hybrid materials are designed with sustainability and societal responsibility embedded from the outset. Future work will refine assessment frameworks and align them with emerging European SSbD guidelines.

DISSEMINATION, COMMUNICATION AND EXPLOITATION

SAFARI has established a comprehensive framework to disseminate project results, engage stakeholders and prepare future exploitation of innovations. A structured outreach strategy targets researchers, industry, policymakers and the general public through digital platforms, events, publications and collaboration with the Graphene Flagship. Progress is monitored through key performance indicators and internal tracking tools to ensure effective knowledge transfer. In parallel, exploitation activities have begun, including identification of key exploitable results, market and business analyses and intellectual property planning. These actions lay the groundwork for future commercialisation of safe and sustainable 2D material technologies developed within SAFARI. In the next phase, stakeholder engagement and industrial collaboration will be intensified to support technology transfer and market uptake.

During its two years operation, SAFARI, through the active involvement of its partners, was represented in various important, international scientific conferences and congresses. From LOPEC, Materials Week, the Graphene Week 2024 and 2025, the SSbD Bootcamp, the SSbD2025 conference, the Electronica Fair 2024, to the SETAC Europe 35th Annual Meeting, the SENTIATECH Congress, the Sustainable Printed Electronics 2025 we did not miss a chance to share and present our results to the scientific community. These engagements facilitate direct interaction with scientific peers, industrial stakeholders, regulatory bodies, and innovation

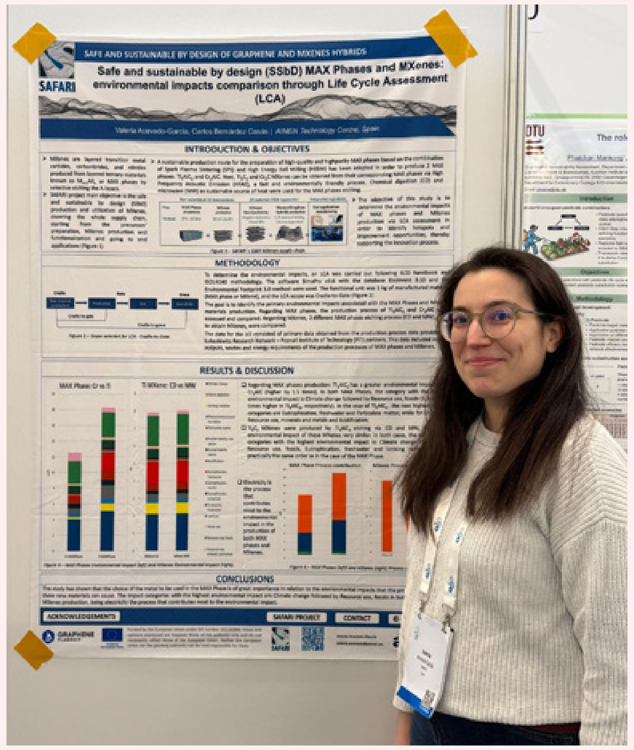

Figure 2. SAFARI at the SETAC Europe 2025.

communities, strengthening collaboration opportunities and positioning SAFARI as an active contributor within the broader Graphene Flagship landscape.

The consortium also organised and participated in various workshops such as the "Advancing Sustainability in 2D Materials" or the "Innovating Europe´s 2D Materials Future" organised at the premises of our partner Creative Nano together with fellow Graphene Flagship projects GRAPHERGIA and 2D-BioPAD.

A huge part of SAFARI's dissemination and communications activities are the digital and online presence in different platforms starting with our official website, our social media channels such as LinkedIn, Facebook and X as well as our videos on YouTube with interviews (Part 1, Part 2, Part 3) and insights into the project by our partners.

Additionally, we produce newsletters on a frequent basis where we highlight our latest achievements such as news from our labs, collaborations, event announcements and results obtained. So far, four SAFARI newsletter have been shared with the public (Newsletter 1, Newsletter 2, Newsletter 3, Newsletter 4). These newsletters not only disseminate technical achievements but also create an ongoing dialogue with researchers, industry, policymakers and the interested public, helping transform SAFARI from a research project into a visible and recognisable network in the 2D materials field.

SAFARI is also proud of its first scientific publication which was released in April 2025 entitled "Synthesis of ternary and quaternary MAX phases in Ti/Cr/Nb/V-Al-C system by high energy ball milling and pressureless spark plasma sintering" by our coordination team Poznań Institute of Technology. Finally, we are eager to share our knowledge, results and market insights of the technologies developed within SAFARI with the general public by creating posts and articles in our newsletters in an easy-to-understand format ensuring that our research does not just stay in labs within the scientific community:

Figure 3. Workshop on “Advancing Sustainability in 2D Materials”.

- Unlocking the Market Potential of SAFARI
- The goals of our Project
- What makes 2D materials truly extraordinary?
- MXenes & Graphene Market Insights
- SAFARI’s socio-economic focus
- A brief history of MXenes
- SAFARI’s end products

Parallel to dissemination, SAFARI has initiated exploitation planning to ensure that project results progress beyond research. Key exploitable results are being identified and monitored, supported by market analyses, business modelling, patent landscape assessments and intellectual property planning. This structured approach links community-building and visibility efforts with long-term innovation and industrial uptake pathways, ensuring that SAFARI’s outcomes are prepared for real-world impact.

POWERED BY THE GRAPHENE FLAGSHIP

Being part of the Graphene Flagship has provided SAFARI with a strong platform for visibility, collaboration and knowledge exchange within Europe’s leading 2D materials community. The initiative’s established network of research institutions, industry partners and innovation activities has enabled SAFARI to connect with complementary projects, share expertise and align its work with broader European roadmaps in graphene and related materials. Through this platform, SAFARI has actively contributed to major Graphene Flagship events, including participation in Graphene Week 2024 with a poster and presentation, and a leading role at Graphene Week 2025 by organising a dedicated workshop and chairing a technical session. Collaboration with other Graphene Flagship projects has also resulted in joint dissemination outputs, such as a common article on “2D Materials Innovation for Biomedical Applications”, as well as shared workshops and thematic discussions under the Graphene Flagship umbrella. Overall, this close integration within the Graphene Flagship ecosystem has strengthened SAFARI’s scientific impact, expanded its stakeholder network and supported the translation of project results toward real-world applications.

ON THE HORIZON

In the coming year, SAFARI will focus on consolidating its technological developments and advancing them closer to real-world application. Key priorities include further scaling up safe and sustainable MXene production processes, refining graphene–MXene hybrid materials for targeted end-use demonstrations, and completing comprehensive safety, environmental and performance assessments. Continued efforts will be dedicated to integrating digital modelling and decision-support tools to guide material design, as well as strengthening life cycle and sustainability evaluations. At the same time, SAFARI will expand collaboration with industrial stakeholders and Graphene Flagship partners to validate application prototypes and identify commercialisation pathways. Future challenges include balancing material performance with safety and sustainability requirements, ensuring reproducibility at larger production scales and preparing regulatory and market readiness for next generation 2D material technologies.

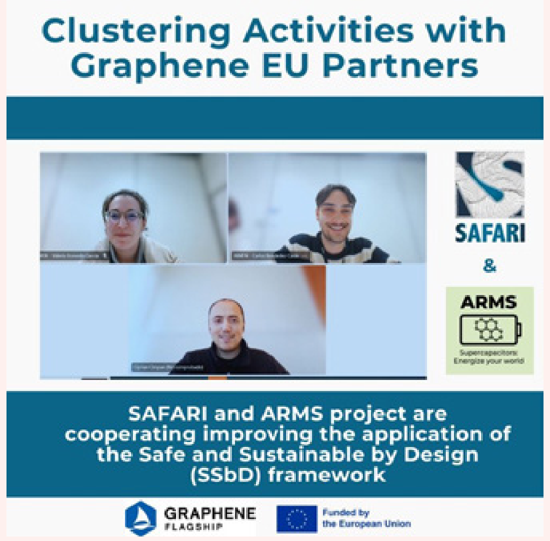

Figure 4. Clustering activities with Graphene Flagship partners.

Figure 5. Online article “2D Materials Innovation for Biomedical Applications”.

Figure 6. “Safe and Sustainable by Design 2D Materials: Manufacturing Processes and Applications in Energy, Electronics, and Biotechnology” at Graphene Week 2025.

SURPRISE ME

Creative Nano has developed an environmentally friendly molten salt process to synthesise Ti$_3$C$_2$T$_x$ MXenes, completely eliminating the need for HF, fluoride salts and inert conditions. The produced MXenes were then functionalised with APTES and polypyrrole, and coated onto glassy carbon electrodes, resulting in a significant enhancement in current response. As part of the SAFARI Project, these advancements are being applied to develop highly sensitive electrodes for glucose and lactate detection, as well as conductive inks and EMI shielding paints, demonstrating the potential of MXenes for both biomedical and industrial applications.

Safe by Design

PROJECT COORDINATOR

Dariusz Garbiec, Poznanski Institute of Technology, Poland

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ISQ Group, Portugal
AIMEN Technology Center, Spain
Danish Technological Institute, Denmark
Israel Aerospace Industries Ltd., Israel
ThinkWorks BV, Netherlands
AXIA Innovation GmbH, Germany
Metrohm DropSens SL, Spain

ASSOCIATED MEMBERS

Graphenest SA
Avanzare Innovacion Tecnologica SL
Sabanci University

SAFARI

Exciting young researchers

The Graphene Flagship is dedicated to fostering the next generation of graphene and 2D materials researchers and innovators. These young researchers are already distinguishing themselves in the community as poster winners, impact leaders and trend setters.

Dmitriy Poteryayev
Istituto Italiano di Tecnologia
Graphene Week 2025 poster winner: Processing

"Currently, our team is working on several projects involving AI, specifically AI-assisted growth optimisation of various materials and characterisation via Raman spectroscopy. The overall goal for us is to approach scalability and consistency of material synthesis using reliable feedback from characterisation. We want to reach wafer scale high quality graphene as well as other 2D materials.

"I feel the importance of my research is in the way that it can change the game rules of the field, once the long-standing scalability problem is solved. It can affect the way semiconductor devices are being made. It is hard to predict the full extent of the impact, but I am certain it will transform our everyday lives.

"My experience at Graphene Week 2025 was breathtaking. High level organisation, relevant talks, so many increadible people I've met. I'm glad I got the opportunity to be part of this big and warm community."

Teissir Ben Ammar
Blackleaf
Graphene Week 2025 poster winner: Applications

"The first time I imaged cells interacting with graphene, first with scanning electron microscopy, then with confocal fluorescence. I was genuinely fascinated by the beauty of what I saw: the cell shapes, the fine structures and especially the brightly coloured compartments revealed by the fluorescent markers.

"Winning the Graphene Week Poster Award was a great honour and a wonderful recognition. I would like to thank the entire graphene community for their support and inspiration. The collaborative spirit I observed during Graphene Week was exceptional, and I'm excited to contribute to advancing 2D materials research and its applications in healthcare. I encourage other early career researchers to participate in these events and engage with this vibrant community."

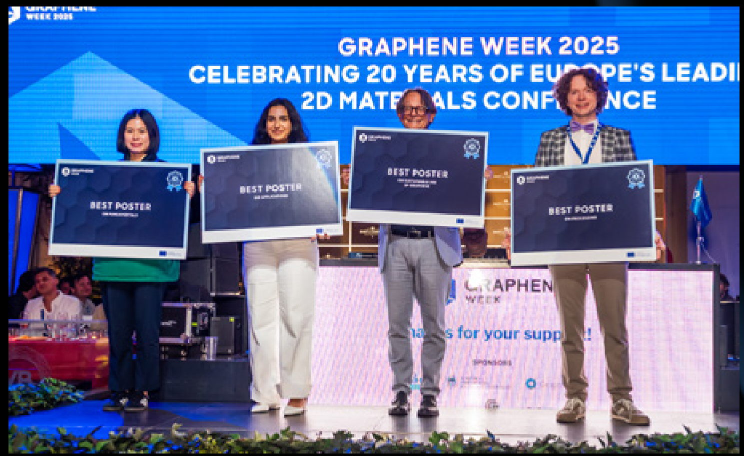
Alessandro Calza
University of Bologna
Graphene Week 2025 poster winner: Sustainable use of graphene

"My research focuses on pollution, which is a pressing issue in modern society. Many emerging contaminants are difficult to remove using traditional water treatment methods. By combining modelling and experiments, we aim to better understand how graphene oxide captures these pollutants and to improve future materials for waste-water remediation.

"I would love to work on integrating AI with molecular dynamics to predict adsorption or interaction properties of functionalised graphene directly from experimental data. It would be a good way to connect simulations and experiments into a single, more efficient predictive framework.

"Winning the Graphene Week poster award was unexpected, but very rewarding. It gave me a chance to look back and appreciate how much progress I had made during my PhD. It's always nice to see your work recognised by the scientific community."

> Winning the Graphene Week poster award was unexpected, but very rewarding."
>
> Alessandro Calza



Chenda Vong
Sogang University
Graphene Week 2025 impact leader

"I enjoy fabricating new, exciting material combinations and uncovering their physical meaning through phonon interactions, especially when a simple Raman peak reveals complex interlayer phenomena. Some combinations exhibit surprising properties that can become real game-changers for engineers.

"By understanding how the material interacts within layered stacking systems, we can design more reliable and efficient devices. This research provides fundamental insight into how thin and thick layers interact, supporting the future of device engineering by improving efficiency and stability.

"Graphene Week 2025 was more than just a conference; it was a place to share research discoveries and to connect with a diverse research community. The event inspired me and gave me the opportunity to meet many scholars and researchers, as well as to build meaningful connections. It was an unforgettable experience."

Sina Dörr
University of Kassel
Graphene Week 2025 impact leader

"My research focuses on the surface modification of raindrop triboelectric nanogenerators (RD-TENGs), in order to improve the overall performance. The main goal is to gain enough energy to improve solar cells with an additional coating on top. I think this research is important, as the demand for energy rises continuously and developing new ways of producing green and renewable energy are of high interest. The use of easy fabrication methods is favorable and can be applied for our RD-TENG devices. Gaining energy out of raindrops would be a great way to supplement the decreasing solar cell efficiency on rainy days and build all-weather systems.

"Graphene Week 2025 was my first big conference, and it was amazing to see all the different levels of research coming together here, from fundamental research to applications and devices. Talking to people who established a startup from scratch was interesting and one of my best parts of this conference."

Mansun Wang
National Physical Laboratory
Graphene Week 2025 poster winner: Fundamentals

"A memorable moment for me was during a late-night lab session when a measurement I had repeated many times finally produced a clean and interpretable spectrum. There was nothing extraordinary about the result itself, but that small breakthrough reminded me how progress in 2D materials often comes from persistence, refining experimental conditions and learning to distinguish real signals from artefacts. It wasn't a dramatic discovery, just a quiet but satisfying reminder of why careful measurement matters.

"Winning the Poster Award was an honour and a great moment of encouragement. It felt rewarding to have my work recognised by a community that I admire."

GATEPOST

Shaping the future of IoT and 5G/6G through energy-efficient, graphene-based photonics for data processing and network security

GATEPOST IS ADVANCING next-generation technologies that enhance the security and performance of the Internet of Things (IoT). By integrating graphene and other two-dimensional (2D) materials with standard silicon nitride CMOS technology, the project is creating ultra-fast, energy-efficient computing and memory devices that can meet the growing demands of connected devices. Central to this approach is the use of light for information processing, enabling high-throughput, low-latency computation.

These innovations are designed to support real-world applications such as smart cities, autonomous vehicles and next generation 5G and 6G networks. Bringing together leading experts from across Europe, GATEPOST is shaping the future of computing by delivering solutions that are not only powerful and efficient but also secure, resilient and ready for the interconnected digital landscape of tomorrow.

HIGHLIGHTS

Over the past reporting period, GATEPOST reached several important technical and organisational milestones. A key achievement was the successful fabrication of the first photonic integrated GATEPOST chips, unveiled following extensive design and process development activities. The chip, based on graphene integrated on silicon nitride technology and fabricated on a 200 mm platform, enabled the validation of multiple building blocks relevant to logic, neuromorphic computing and optical memory.

In parallel, the project consortium presented its scientific results at major international conferences and through peer-reviewed publications, marking an important step in establishing GATEPOST's scientific visibility. Progress was made across all work packages, reflecting the effectiveness of the project's interdisciplinary and collaborative approach.

PROGRESS IN 2025

During the past year, GATEPOST has continued to advance its graphene-based all-optical platform for secure and efficient IoT computing, following an agile work plan structured around six work packages. Four of these packages focus on scientific research, with project partners collaborating across disciplines to drive innovation throughout the platform.

Several key milestones have been successfully achieved to date. These include the completion of the component-level design, the first prototype generation of the graphene process design kit (PDK), the establishment of baseline processes and the successful execution of the first tape-out run, which allowed the first integrated photonic circuits to be fabricated and tested. These achievements mark important steps toward building fully integrated, high-performance and energy-efficient devices.

> Over the past year, GATEPOST has made major strides in the development of a graphene-based all-optical chip for IoT data processing and security. With key development milestones achieved, the project is now entering the validation phase, testing the performance and reliability of the chip as we advance toward practical, secure and efficient solutions for the interconnected digital future".

Mindaugas Lukošius
Project Coordinator
IHP GmbH – Leibniz Institute for High Performance Microelectronics

The project is organised into three phases. In the conception phase, fundamental requirements are defined and the groundwork for development is laid, primarily under work package two, System Level/Device Level Modelling and Design. During the development phase, iterative collaboration between work package three, 200 mm Graphene Process Development and Integration, and work package four, System Integration, ensures that design, fabrication and integration activities are closely linked. Key components, such as ultra-fast all-optical logic gates and optical neurons, are implemented through multiple tape-out runs. In the validation phase, prototypes are built and targeted key performance indicators are evaluated under work package five, Demonstration and Validation, with results feeding back into work packages three and four to refine the designs. Work package one, Project Management, supports all phases by coordinating activities, ensuring smooth collaboration, and maintaining progress tracking, while work package six, Dissemination and Exploitation, ensures that results are communicated to the wider scientific and industrial community.

This structured, agile approach allows GATEPOST to systematically advance all technical aspects of the project, ensuring that each phase builds upon the previous one. By the end of 2025, these efforts have brought the project closer to a fully validated, high-performance, energy-efficient and secure computing platform for next-generation IoT applications.

Work Package Achievements
Building on the foundation laid in the early project phases, GATEPOST achieved significant technical progress across its core work packages in 2025. System Level/Device Level Modelling and Design provided the initial framework by completing the component-level design and producing the first prototype of the graphene process design kit (PDK). This ensured consistent standards across all partners and laid the groundwork for fabrication and testing.

GATEPOST's first bi-annual meeting took place in April 2025 in Brussels, Belgium. Credit: HPE, Matěj Hejda

The project's work in 200 mm Graphene Process Development and Integration was at the heart of this progress. The first baseline processes were completed, and the initial wafer was successfully taped out, enabling validation of individual components, including logic, neuromorphic and memory devices. Optical and electrical measurements confirmed key performance parameters such as loss, saturable absorption, modulation depth, noise, bandwidth and overall device performance. Subsequently, a second tape-out run focused on neuromorphic computing and memory devices, with comprehensive testing verifying their performance. These accomplishments mark important steps toward fully integrated, high-performance graphene-based photonic devices.

Building on these results, System Integration advanced the combination of individual components into functional subsystems, preparing the platform for full-scale demonstration. Demonstration and Validation is now preparing the evaluation of the prototypes against targeted key performance indicators, feeding results back into the development cycle to refine fabrication and integration processes. Taken together, these achievements highlight how GATEPOST is steadily progressing toward its goal of delivering a fully validated, energy-efficient, secure and high-performance computing platform capable of supporting the next generation of IoT applications.

Throughout the last year, regular in-person meetings with all partners have been particularly important. In spring, the consortium met at HPE in Brussels, and in autumn, the meeting took place at Akhetonics in Munich. These gatherings fostered direct exchange, strengthened collaboration and ensured alignment across disciplines and work packages.

DISSEMINATION AND EXPLOITATION

The GATEPOST consortium has made strong progress in disseminating its results and building visibility within the scientific and industrial communities. Four peer-reviewed Open Access publications in high-impact journals highlight key advances across the project: photonic neural networks and optics-informed deep learning,[1] graphene-based modulator design and optimisation for integrated photonics,[2] and nonlinear optical vector processing using silicon photonic circuits for high-speed memory and string similarity functions,[3] as well as the demonstration of a high-performance hyperdimensional photonic AI accelerator achieving 262 TOPS, illustrating the scalability and system-level potential of photonic computing architectures.[4] In addition, the consortium produced three non-public publications, two preprints and eleven conference proceedings, demonstrating sustained engagement with the scientific community.

Beyond publications, GATEPOST has strengthened visibility through participation in 20 international conferences and industrial fairs, as well as through poster presentations and workshops. For example, Daniele Capista from IHP presented a poster at Graphene Week 2025 in Vicenza, Italy, titled "Evaluation of Contact Architectures for Large-Area CVD Graphene Integration in CMOS-Compatible Photonic Platforms". A particularly notable highlight was GATEPOST's participation at ECOC 2025 in Copenhagen, one of the world's leading conferences on optical communication and photonics. Two scientific papers from the WinPhoS Research Group were accepted for presentation, titled "20 Gb/s Quaternary Content Addressable Memory using Silicon Photonics" and "Euclidean Distance Calculation Engine using an Analog Silicon Photonic Tensor Core", demonstrating the consortium's cutting-edge research and collaborative achievements.

To reach a broader audience, the consortium released two short video interviews, in which Michael Kissner, co-founder of project partner Akhetonics, presented GATEPOST, providing an accessible overview of the project's objectives and achievements. In addition, Akhetonics produced a documentary titled "Photonic Chips are coming faster than anyone expected", published on the YouTube channel *Europe's Foundry*. The video received numerous views and comments within days, demonstrating that GATEPOST's work is highly topical and resonates beyond the scientific community.

In parallel, GATEPOST maintains an active presence on LinkedIn, where regular updates on project milestones, events and partner activities continue to build and engage a growing community interested in graphene-based photonics and all-optical computing.

POWERED BY THE GRAPHENE FLAGSHIP

GATEPOST benefits from being part of the Graphene Flagship, which provides crucial support for the project. In 2025, the consortium actively participated in Graphene Week in Vicenza, Italy, contributing to the scientific programme and community engagement. A joint workshop on "2D Materials for Electronic, Photonic, and Quantum Applications" was co-organised with the 2D-PL and 2DNeuralVision projects. The workshop was moderated by Mindaugas Lukošius (IHP), while Leonardo del Bino, Co-Founder of Akhetonics, presented a talk titled "Graphene for Photonics: at the interface between Material

Daniele Capista (IHP) presenting a GATEPOST poster at Graphene Week 2025 in Vicenza, Italy, and discussing project results with attendees. Credit: IHP, Mindaugas Lukošius

Joint Workshop on "2D Materials for Electronic, Photonic, and Quantum Applications" at Graphene Week 2025, Vicenza, Italy: Pierre Morin (Belgium, IMEC), Ivana Cavaliere (Spain, ICFO), Mindaugas Lukošius (Germany, IHP GmbH), Inge Asselberghs, (Belgium, IMEC), Theresia Knobloch (Austria, Technical University Wien), Yujie Guo (Belgium, IMEC/Ghent University), Sarah Riazimehr (Germany, Oxford Instruments Plasma Technology) and Leonardo Del Bino (Germany, Akhetonics GmbH). Credit: IHP, Daniele Capista

Science and Integrated Optics" and participated in the subsequent discussion with the audience. In addition, Mindaugas Lukošius presented "Towards graphene photonic platform on 200 mm silicon wafers" in a parallel session on "Electronics, Photonics, Optoelectronics."

Beyond Graphene Week, GATEPOST benefits from ongoing engagement with the Graphene Flagship network, collaborating with other projects, accessing advanced 2D-materials infrastructure and state-of-the-art facilities and participating in networking and thematic meetings. This support enhances knowledge exchange, cross-project collaboration, alignment with European research priorities and the dissemination of project results to scientific and industrial communities. In addition, it provides opportunities for training and mentoring of young researchers, fostering the next generation of scientists and engineers in graphene-based photonics and all-optical computing. These collaborations and resources allow GATEPOST to translate cutting-edge graphene research into impactful technological solutions.

STRATEGIC VISIBILITY AND EUROPEAN IMPACT

Beyond its scientific and technological progress, GATEPOST has also gained visibility at a strategic policy level, underlining its relevance for Europe's technological sovereignty. In 2025, project partner Akhetonics presented graphene-based photonic wafer technology developed within GATEPOST to senior German politicians, including Federal Minister of Defence Boris Pistorius. The exchange highlighted the potential of photonic processors as a key enabling technology for high-performance and AI computing, as well as the importance of building resilient, EU-based value chains for advanced micro- and photonic systems. The showcased wafer, fully manufactured in Europe, exemplifies how graphene-enabled photonic technologies can combine cutting-edge research with industrial scalability and strategic relevance. This high-level engagement reflects the growing recognition of GATEPOST's contribution to strengthening Europe's position in secure, energy-efficient computing and advanced processor technologies.

ON THE HORIZON

In the coming year, GATEPOST will focus on further advancing the development and validation of its graphene-based all-optical platform. Building on the progress made in 2025, the project will continue to refine prototypes, optimise device performance and address remaining technical challenges, including reducing losses, improving bandwidth and enhancing energy efficiency. System integration will be strengthened, ensuring that individual components, such as all-optical logic gates, optical neurons, neuromorphic memory elements and look-up functions, work seamlessly together in preparation for large-scale demonstrations.

Key milestones on the project's agenda include the verification of the SCL and the graphene process design kit (PDK), high-speed optical clock operation and the successful implementation of neuromorphic computing, optical memory and look-up functionalities, followed by comprehensive system integration testing. Achieving these milestones is essential to demonstrating the platform's readiness for next-generation IoT applications and to providing a robust foundation for energy-efficient, secure and high-performance all-optical computing systems.

GATEPOST will also continue its active dissemination and engagement efforts. Based on the progress achieved so far, the consortium is on track to meet its dissemination objectives. Further Open Access papers, scientific publications, conference contributions, workshops, videos and outreach activities are planned for the upcoming project period, reinforcing GATEPOST's role in advancing secure, high-performance and energy-efficient graphene-based photonic technologies.

Finally, joint workshops and collaborative events are planned with other Graphene Flagship projects, providing platforms for knowledge exchange, fostering interdisciplinary cooperation and highlighting GATEPOST's progress. These activities will strengthen the project's connections across the European photonics and graphene research landscape, ensuring continued alignment with the initiative's broader objectives and European research priorities.

Impressions from the joint GATEPOST workshop: Leonardo del Bino (Akhetonics GmbH) on the left and Mindaugas Lukošius (IHP) on the right during their contributions to the session. Credit: Giò Tarantini/ Gruppo Tonello

A closer look at Europe's innovation: German Defence Minister Boris Pistorius with the GATEPOST graphene-based wafer, alongside Michael Kissner, co-founder of Akhetonics. Credit: Akhetonics GmbH

SURPRISE ME

A striking and unexpected result from the GATEPOST project came from project partner Akhetonics, whose documentary "Photonic Chips Are Coming Faster Than Anyone Expected", published on the Europe's Foundry Channel in mid-December 2025, initially received over 83,000 views and more than 550 comments within just five days. Since then, the video's reach has grown significantly, reflecting sustained interest from both the scientific community and the broader public.

Within GATEPOST, Akhetonics is responsible for the design, simulation and modelling of linear and non-linear graphene-based components, contributing directly to the development of the project's all-optical platform for next-generation communication, security and high-performance computing technologies in Europe. The documentary's repeated presentation of the GATEPOST chips clearly illustrates the tangible outcomes of the project's interdisciplinary efforts.

This achievement surprised the team both in terms of public attention and the technical performance of the platform, illustrating how cutting-edge research can generate broad interest beyond the scientific community and reinforce the relevance of graphene-enabled photonics for European technology leadership.

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Electronics and Photonics

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GATEPOST PROJECT

2DNEURALVISION

A Horizon Europe initiative pioneering low-power, 2D-materials-based computer vision systems for robust performance in low-light and adverse weather conditions

THE 2DNEURALVISION PROJECT is a collaborative European research initiative aimed at revolutionising how machines "see" in challenging environments. Over three years, seven leading institutions from four countries are working together to create ultra-efficient, miniaturised camera systems and smart visual processors that continue to work reliably in low-light or poor weather conditions. By using advanced two-dimensional (2D) materials like graphene, these lighter, more powerful sensors and optical computing elements will pave the way for smarter, safer applications, from self-driving cars and service robots to AR/VR devices, while reinforcing Europe's leadership in the digital-technology supply chain.

> "Over the last two years, the 2DNeuralVision partners have worked together and made significant leaps in developing technologies for low-cost, low-power consumption machine vision for automotive applications and beyond. We have seen progress on areas from the synthesis of new quantum dot materials to wafer scale processes of 2D materials, to CMOS integration and design and implementation of optical neural networks enabled by graphene. As we enter the last year of our project, we are excited to see how those pieces of the puzzle are put together towards our end goal."

Gerasimos Konstantanos
Project Coordinator
ICFO

PROGRESS IN 2025

Spec definition and validation
In work package two, spec definition and validation, we collected the needed specifications for the two demonstrators, namely a quantum dot-based imager chip containing TMDC and a graphene-based optical neural network chip. The specifications are detailed in the confidential part of the documentation. We also identified use cases which will be validated by end of the project.

The quantum-dot-based imager chip is working in the short-wave infrared which has an advantage in supressing optical scattering occurring in harsh weather like fog, dust and rain. The smaller the particles the bigger the effect, this was shown in a controlled test environment. Additionally, increasing the spectral range of the camera enables the customer to use additional light sources in the short-wave infrared without blinding other road users. Surprisingly pedestrians wearing dark textiles can be seen much better within the short-wave infrared because textiles usually reflect a lot of light in that spectral range and their outfit thus appears bright instead of dark. All together this is increasing safety for vulnerable road users. Lead-free quantum dots are the enabler technology to bring down fabrication cost of short-wave infrared sensitive cameras. To validate the benefits of this technology and facilitate later application, a test car was built to compare standard automotive RGB cameras with cameras working in the short-wave infrared. The data set that was collected will be published at the end of the project and can be used to train neural networks for object detection and classification.

Besides the new camera technology, optical computing has great potential. Real-time data processing at low energy consumption will be needed for example in self-driving cars. Therefore, the second demonstrator is an optical neural network. In 2025 a process design kit was developed containing graphene-based elements. The chip was fabricated (see also work package four). To validate its performance, a set of criteria was collected and formulated in the specification document. These criteria target operation speed and energy efficiency of the chip. Suitable characteristics for identifying an artificial neural network architecture and apt training data for evaluating the optical neural net are presented there as well.

In the end, the optical neural net will be evaluated on image data with an image classification and/or segmentation model.

Image sensor component development
Work package three, image sensor component development, has made strong and encouraging progress across all three development areas. Significant breakthroughs were achieved in the synthesis of lead-free colloidal quantum dots and in their successful integration with CMOS technology to develop colloidal quantum dot-based wide-spectrum image sensors. Along the way, major technical challenges were overcome in each area, turning obstacles into valuable insights that have strengthened the project and accelerated its momentum toward practical, scalable solutions.

This year has been a very productive and fruitful period on the synthesis of III-V CQDs for their application in SWIR photodetectors and image sensors. We have identified – *to our surprise* – that one key challenge on the synthesis of monodisperse InSb CQDs has been a fusion process that takes place during the synthesis. This is a mechanism that is responsible for the broadening of absorption and the creation of low energy absorption tails. We developed a new synthetic protocol for such CQDs that avoided this fusion process yielding InSb CQDs of exceptional quality in terms of size dispersion and absorption characteristics.

Work progressed on the integration of CMOS with a two-dimensional molybdenum disulfide (MoS_2) layer. A redesign of the overlay structures enabled much finer alignment and improved lithography control. The initial batch of MoS_2 transfer onto the main CMOS wafers unfortunately revealed contamination that halted further processing. A pre-planned backup batch of wafers was successfully used to continue the process. To minimise future risks, we split the wafers into smaller batches and replaced and inspected all transfer equipment before

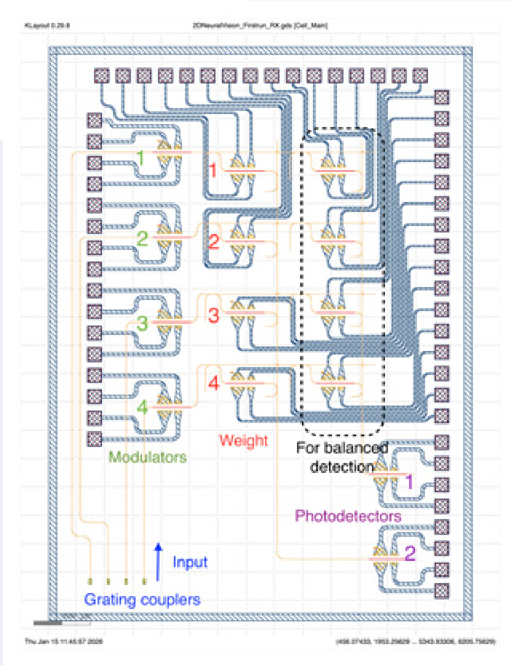


Figure 1. Layout of the 4×2 ONN chip.
Credit: University of Heidelberg

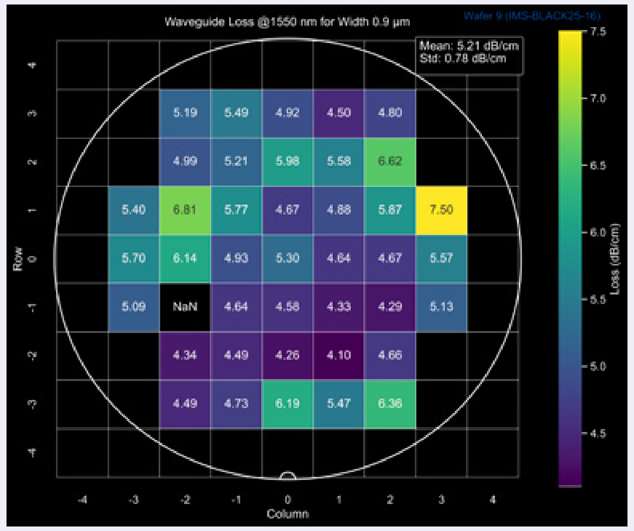
resuming MoS_2 transfer. Developments are on track to achieve the planned delivery date for next year.

We also achieved an important milestone and deliverable on the image sensor integration front. The development of InSb CQD active layer deposition on CMOS substrates encountered issues with delamination. Optimising ligand exchange strategies and implementing surface modifications solved the delamination issues. We combined process module development from previous years (such as lithographic CQD patterning) with these newly developed InSb CQD active layer process modules to show the first InSb CQD-based high definition (1280 x 720) wide-spectrum image sensor.

Optical neural network component development
After finalising the process design kit (PDK) in work package four, optical neural network component development, including detailed specifications collected from all partners, we designed, fabricated and characterised a 4×2 optical neural network (ONN) chip (Figure 1) based on *SiNx* photonics with integrated graphene-based active components. A key innovation in our approach is the use of graphene-based modulators and photodetectors. Compared to alternative active materials, graphene offers several advantages: its ultrafast carrier dynamics enable high-speed modulation, its broadband optical absorption supports operation across a wide spectral range, and its strong electro-optic tunability allows for compact, low-power devices. Moreover, graphene's compatibility with established SiNx photonic platforms facilitates monolithic integration, making it a superior choice for scalable ONN implementations.

Passive optical components play a critical role in optical communication systems by facilitating the routing, coupling, splitting and controlling of light signals without requiring external power. The optical losses of the passive *SiNx* waveguides (Figure 2) and grating couplers (Figure 3) were measured on wafer-level demonstrating elevated yet still acceptable levels.

For the active graphene-based modulators (weights), we were able to demonstrate comparable modulation efficiency (0.001 dB/V*um) as state-of-the art lithium niobate modulators. Photodetectors yielded lower responsivity than expected



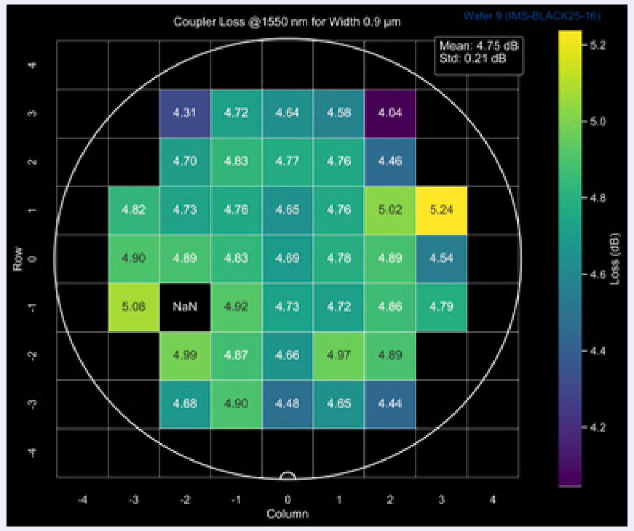


Figure 2. Wafer map of the optical waveguide propagation loss @ 1550 nm.
Credit: Black Semiconductor
Figure 3 (below). Wafer map of the optical grating coupler insertion loss @ 1550 nm. Credit: Black Semiconductor

(28 mA/W) and 3 dB bandwidth (44 GHz) due to non-optimised, high contact resistances and incomplete graphene encapsulation. Nonetheless, these devices are operational and can be used to test core functions of the envisioned ONN system including running convolution operations, edge detection tasks and inference tests using standard benchmarks such as MNIST and CIFAR-10, assessing accuracy, speed and energy efficiency. Results will inform future optimisation pathways. Finally, fabricated chips were delivered to work package five for further system integration.

System integration
Work package five, optical neural network component development, focused on system integration, beginning with chip-level integration of the ONN and progressing to full system-level integration of a complete photonic accelerator platform. After finalisation of the external-control architecture, defining the interaction between electronics, optics and software, the design, integration and characterisation of a rack-mount photonic tensor accelerator were carried out, enabling the ONN to be accessed through a standard machine-learning interface. At the hardware level, the ONN chip is driven by a micro-ring frequency-comb source and controlled by a Xilinx ZCU216 RFSoC (combining high-speed data converters and FPGA logic). As shown in Figure 4, the ONN is wire-bonded to a custom photonic circuit board, coupled via a glued fibre array, and assembled into a standard 19-inch rack unit with RF connectors for high-speed I/O and debugging.

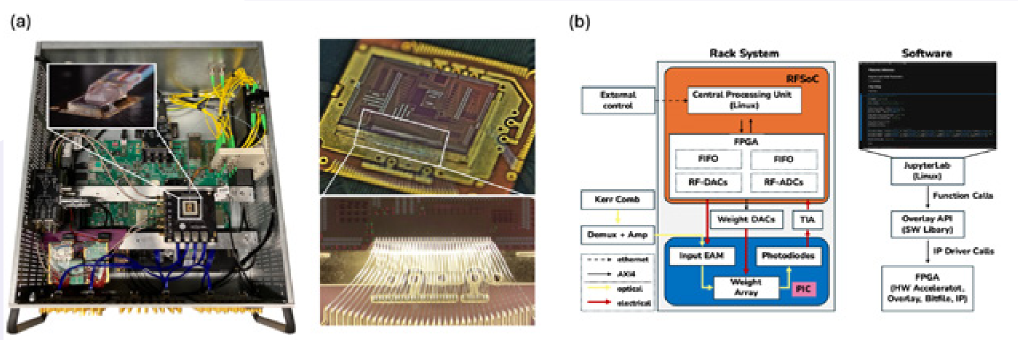


Figure 4. (a) Photonic hardware accelerator in a 19-inch rack housing, close up of the glued fibre array, the photonic tensor core, wire bonds to the pcb, chip level view of the optical processor and the frequency comb. (b) Schematic overview of the convolution system, hardware on the left, software on the right. Credit: University of Heidelberg

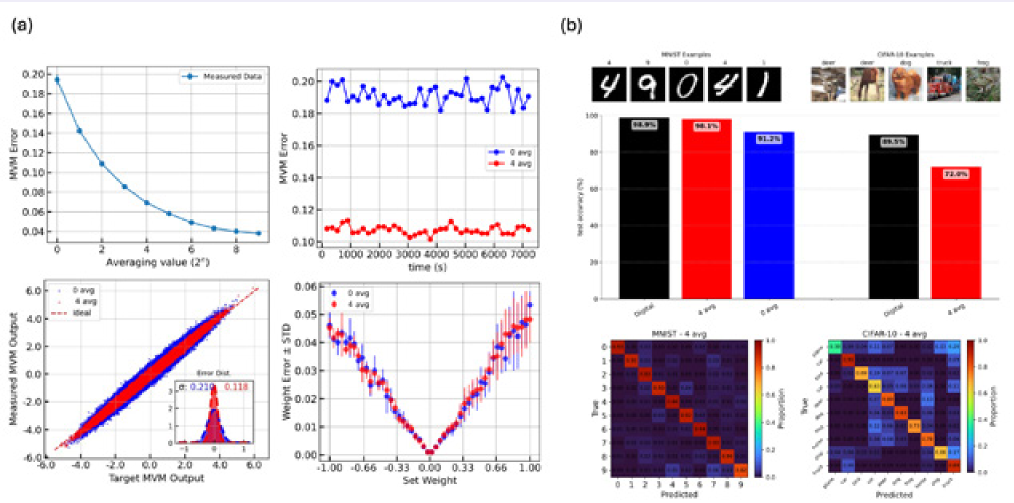


Figure 5. (a) Characterisation data of the convolution system. MVM error vs averages, stability over time, cloud plot of MVM precision with error distribution, weight error. (b) Test accuracies of both neural networks for MNIST and CIFAR-10. Digital in black 4 avg mode in red and 0 avg in blue. Confusion Matrices are shown for 4 avg mode. Credit: University of Heidelberg

The system is built around an incoherent optical crossbar "photonic tensor core," in which electro-absorption modulators encode both input activations and weights as intensity variations, while on-chip photodiodes perform the summation directly in the optical domain, enabling matrix–vector multiplications (MVM) and convolution operations at photonic speed and efficiency. Surrounding this core, the complete electronics, control and calibration stack was implemented, including high-speed DAC/ADC pipelines on the RFSoC, FPGA-based streaming logic, and an embedded Linux layer interfaced with Python/PyTorch. From the software perspective, the ONN operates as a drop-in replacement for conventional layers such as nn.Linear and nn.Conv2d, allowing optical acceleration to be used transparently in standard machine-learning workflows. A robust weight-programming and calibration framework was developed. Per-channel calibration maps translate desired neural-network weights into electrical drive signals while compensating for device nonlinearities, wavelength dependence and crosstalk. A balanced readout scheme supports positive and negative weights, and the full weight array can be reprogrammed in approximately 62 ms, enabling rapid reconfiguration between neural-network layers.

Figure 5 illustrates both the numerical accuracy of the calibrated system (Figure 5a) and its practical impact at the application-level (Figure 5b). Figure 5a shows that, after calibration, the error of the comb-driven ONN in performing matrix-vector multiplications decreases from about 20% in a single measurement to roughly 11%, when modest averaging is used, and then approaches an accuracy limit of around 3% with more extensive averaging. This remaining error is mainly caused by inherent hardware effects such as modulator nonlinearity. Figure 5b demonstrates that this level of analogue accuracy is already sufficient for real applications: when the rack-mount ONN is used as a photonic layer within standard neural-network models, it achieves competitive classification performance on common benchmarks such as MNIST and CIFAR-10, closely matching the accuracy of an ideal digital implementation.

Project management

This past year, the coordination team, led by ICFO, ensured smooth execution and strong collaboration across the consortium. Streamlined tools like SharePoint and dedicated mailing lists supported efficient communication, while regular bimonthly calls kept progress on track. Two General Assemblies aligned the roadmap and celebrated achievements.
A successful project review meeting validated progress and reinforced confidence in our strategy. Continuous financial and administrative support guaranteed compliance and efficiency, setting the stage for a successful conclusion. This solid foundation positions the consortium for lasting collaborations and future breakthroughs beyond 2DNeuralVision.

POWERED BY THE GRAPHENE FLAGSHIP

Being part of the Graphene Flagship has been a cornerstone for 2DNeuralVision's success. The collaborative ecosystem has provided access to unparalleled expertise, resources and strategic guidance through roadmap meetings, innovation insights and regular D&C sessions. These interactions have shaped our vision, opened doors for partnerships and amplified our outreach.

Throughout the project, this connection has enabled direct exchanges with leading European research groups and industrial stakeholders working on 2D materials, ensuring that our technological developments align with broader EU strategies on digital and deep tech innovation. Participation in Graphene Flagship working groups has offered valuable opportunities to benchmark our progress, validate our approaches and identify synergies with complementary initiatives.

Moreover, the Graphene Flagship's communication and dissemination channels have significantly boosted the visibility of 2DNeuralVision. Joint newsletters, feature articles, annual reports and event collaborations have allowed us to reach wider audiences, positioning the project as a reference for 2D material-based computer vision systems. The organisation of workshops at major Graphene Flagship events, such as Graphene Week, further strengthened our role in the community and facilitated the transfer of knowledge across research, industry and policy spheres.

As one of the host projects for Graphene Week 2026 in Porto, supported by FI Group on the local committee, we are proud to demonstrate how this synergy accelerates the journey from fundamental research to real-world applications. This upcoming event will serve as a flagship moment for the consortium to showcase our demonstrators, foster new collaborations and highlight how coordinated European efforts can turn cutting-edge materials science into impactful innovation (Figure 6).

Figure 6. Kick-off meeting of Graphene Week 2026 in Porto. Credit: FI Group

ON THE HORIZON

In its final year, 2DNeuralVision will deliver on its promise: integrating 2D material-based sensors with optical neural networks into fully functional prototypes, validated under real-world conditions. We will push for scalability, energy efficiency and robustness, ensuring readiness for industrial adoption in sectors like automotive, AR/VR and robotics.
The road ahead includes ensuring manufacturability at scale, maintaining performance under harsh conditions, achieving interoperability with emerging standards and addressing ethical and regulatory compliance for AI-driven vision systems.
Hosting Graphene Week 2026 in Porto will be critical for igniting collaborations that extend beyond this project. This is not just an ending; it's the launchpad for next-generation vision technologies.

SURPRISE ME

Innovation often comes with unexpected discoveries, and this year work package three delivered one that reshaped our understanding of quantum-dot behaviour. While developing lead-free InSb colloidal quantum dots, the team uncovered a previously unidentified fusion process occurring during synthesis – responsible for the absorption broadening described above. Recognising this hidden mechanism allowed the partners to redesign the synthesis protocol, eliminating the fusion effect and achieving the highly uniform, high-quality CQDs now used in our wide-spectrum image sensor demonstrator. This insight, born from a challenge, became a catalyst for performance gains and a reminder that even in cutting-edge engineering, true breakthroughs often begin with a scientific surprise.

Electronics and Photonics

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2DNeuralVision

GRAPHENE FLAGSHIP ANNUAL REPORT 2025

NEXT-2DIGITS

Integrating graphene and 2D materials to power the next generation of photonic sensing and imaging platforms

THE VISION OF NEXT-2DIGITS is to accelerate the integration of graphene and two-dimensional materials (2DM) into photonic (PIC) and optoelectronic (OEIC) integrated circuits, enabling smaller, faster and more efficient optical devices. Although 2DM offer exceptional optical and electronic properties, their industrial uptake has been impeded owing to the lack of scalable and high quality transfer and integration processes onto wafers and components without introducing defects.[1,2] Next-2Digits introduces clean, scalable integration methods that make it possible to build compact and energy-efficient components for sensing, imaging and environmental monitoring, opening the way to more sustainable and cost-effective photonic technologies.

> Scaling up the digitally controlled transfer of 2D materials is a key step toward their industrialisation."

Ioanna Zergioti
Project Coordinator
National Technical University of Athens

To resolve key limitations in 2DM integration, Next-2Digits employs two wafer-scale additive techniques: a semi-dry transfer process that enables clean, uniform graphene layers across full wafers and laser digital transfer (LDT), a solvent-free, single-step method that places pristine 2DM pixels exactly where needed with no post-processing. These approaches minimise impurities and interfacial defects, resulting in higher carrier mobility, broader bandwidth and more reliable device operation, while also reducing material use, energy consumption and waste. Their impact will be demonstrated across three use cases: a compact LiDAR module for drones, based on a 10 × 10 mm² detector array with 5 µm pitch enabling sub-0.1 mm resolution and 500 GHz detection; a miniaturised greenhouse-gas sensor using graphene-enabled mid-infrared emitters and detectors to achieve ~50 ppm detection limits for real-time biogas monitoring; and an integrated polarisation-diversity receiver (PDR) for optical coherence tomography (OCT) imaging, where graphene-enhanced PICs deliver balanced multi-polarisation detection without bulky optical components.

PROGRESS IN 2025

In 2025, Next-2Digits moved steadily forward towards achieving its core objective of enabling clean, wafer-scale integration of graphene and 2DM into PICs and OEICs, by transitioning from designs and early trials to the fabrication and testing of the first generation of components. The consortium demonstrated full wafer integration of graphene on SOI platforms, enabling the fabrication of graphene photodetectors with record responsivity. In parallel, the integration schemes of the graphene PICs in all three applications have been developed and are ready for deployment. This phase builds directly on the requirements, simulations and platform preparations completed in the previous reporting period, with a focus on manufacturability, reliability and performance in relevant environments.

2D materials growth and platform development
2D materials growth and platform development progressed in material preparation, modelling and platform-level compatibility to support the integration activities in subsequent work packages. Graphenea Semiconductor S.L. (GSEMI) developed graphene, h-BN and graphene/h-BN heterostructures as donor

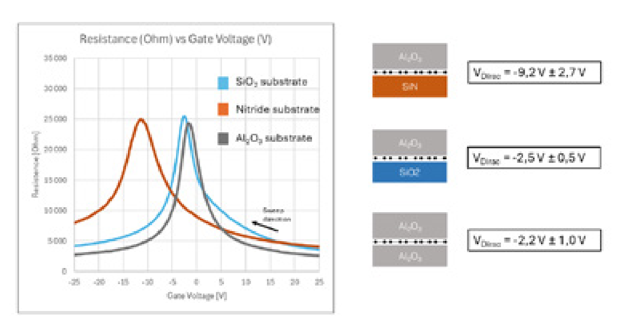

Figure 1. The electrical curve shifts depending on the substrate (SiO_2, nitride, Al_2O_3), showing how the underlying material affects graphene's behaviour. Credit: Silex Microsystems

substrates, which were delivered to National Technical University of Athens (NTUA) for use in laser digital transfer (LDT). In parallel, NTUA carried out density functional theory (DFT) calculations and molecular dynamics simulations to study the optoelectronic properties of graphene and h-BN, as well as printing processes which are relevant to the Next-2Digits project, and the detachment behaviour of boron nitride ribbons and of BN or graphene/BN multilayers from metallic donor substrates. These insights help optimise transfer strategies and understand material-substrate interactions relevant to the project's integration processes.

VTT, Technical Research Centre of Finland, and GSEMI jointly demonstrated the integration of graphene onto a planarised thick SOI platform and fabricated graphene photodetectors with an incorporated escalator structure, which had promising performance. In addition, Silex Microsystems completed the baseline graphene platform in its 200 mm MEMS fab, establishing the foundation for chip fabrication in the LiDAR and gas-sensing demonstrators. Field-effect transistors (FETs) manufactured using graphene transferred via both semi-dry and LDT routes were electrically evaluated, exhibiting n-type behaviour and charge carrier mobilities around 2,000 cm²/V·s, confirming the suitability of the processes for subsequent PIC integration (see Figure 1).

Advances in laser digital transfer and semi-dry integration
Significant progress was made in both transfer methods, which are essential for the clean and precise placement of graphene and other 2DM onto photonic platforms: laser digital transfer

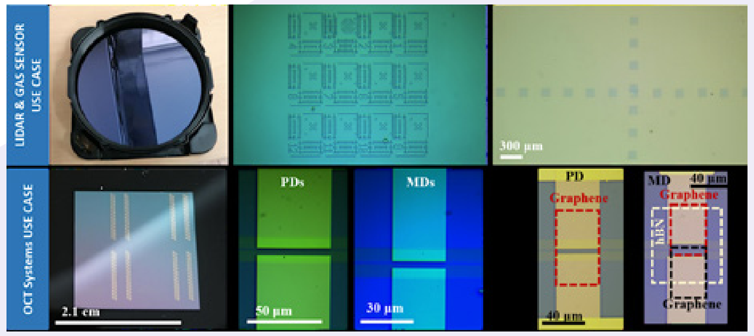

Figure 2. LDT of graphene and graphene/hBN onto a) full SOI wafers used for LiDAR and gas sensor use cases. and b) MDs integrated patterns for OCT systems. Credit: NTUA

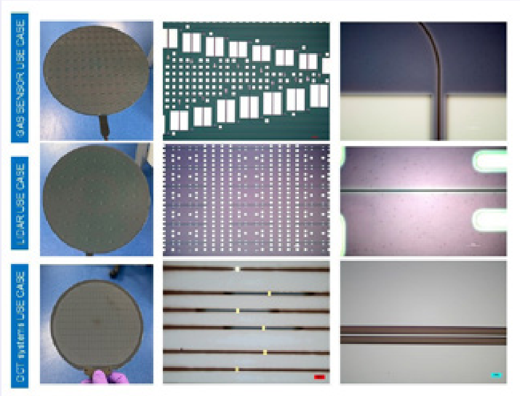

Figure 3. CVD monolayer graphene transferred on 200 mm wafers provided by Silex for LiDAR and gas sensors use cases, and CVD monolayer graphene transferred by semi-dry transfer on a 150 mm wafer for OCT imagers. Credit: Graphenea

(LDT) and semi-dry transfer. NTUA performed multiple laser transfers of single-layer graphene onto 8-inch SOI wafers, creating arrays of hundreds of pixels (Figure 2). The results were encouraging in terms of material integrity and morphological quality, indicating a yield above 90%. LDT was also used to transfer 10–50 µm graphene pixels onto patterned photodetector devices (Figure 2), where early photodetector configurations integrating these pixels were demonstrated and are now under evaluation. NTUA additionally investigated the impact of graphene layer thickness on photodetector performance by fabricating 1–4 layers of graphene using LDT and inspected via optical and scanning electron microscopy, together with Raman spectroscopy. The results showed that single- and few-layer graphene transfers provide consistent film quality and uniformity.

The assembly of graphene/h-BN vertical heterostructures was also investigated to enhance device stability and interface quality, as it serves as a passivation and encapsulation layer that improves graphene's environmental stability and electrical performance. For modulator applications, LDT was employed to integrate stacked graphene/h-BN/graphene architectures onto integrated optical modulator platforms (Figure 3). Work will continue with multi-step transfer refinement and electro-optical testing.

GSEMI performed monolayer graphene transfers on 150 mm wafers (VTT) and 200 mm wafers (Silex Microsystems) using the semi-dry transfer approach.[2] After transfer, optical microscopy was used to ensure the absence of defects and contaminants, and Raman spectroscopy was performed in selected cases to confirm structural quality. Figure 3 shows CVD monolayer graphene transferred onto 200 mm wafers for the LiDAR and gas sensor use cases, and onto a 150 mm wafer for the OCT demonstrator. These results confirm the suitability of semi-dry transfer for high-quality wafer-scale integration.

Photonic chip fabrication for LiDAR, gas sensing and OCT
Fabrication and initial testing of PICs in 2025 progressed across all three application areas. The work focused on the fabrication of the first-generation chips, characterising key building blocks and extracting data to guide the next design iterations.

For Next-2Digits' first use case, the LiDAR demonstrator, Silex Microsystems completed and delivered the first run of graphene-based photodetector chips. These chips incorporate varied waveguide designs and graphene photodiode geometries to optimise light-graphene interaction. Ommatidia Lidar S.L (OMMA) conducted initial characterisation, demonstrating photocurrent generation and responsivity up to ~0.4 A/W. These results validate the device concept and provide concrete input for the next design cycle focused on higher sensitivity and speed.

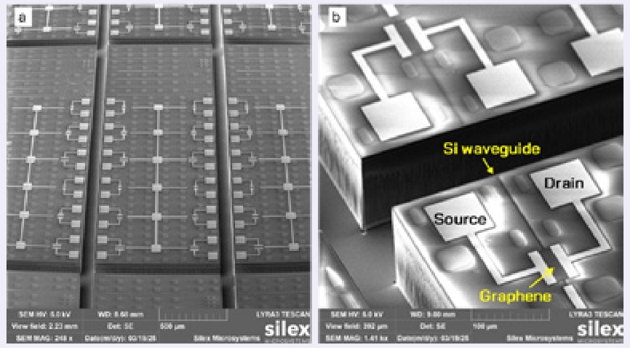

Figure 4. Scanning electron microscopy (SEM) of typical delivered devices of use case 1. a) Dies side by side separated by etched scribe lines. b) Close-up of photodetectors. Credit: Silex Microsystems

For the greenhouse-gas sensor, the second use case, the first fabrication faced challenges in achieving suspended waveguide structures with the required precision. Process optimisations are underway, including design simplifications to improve yield and performance. Despite the challenges, functional test wafers have been produced, enabling preliminary evaluation of passive photonic components.

For the polarisation diversity receiver (PDR) used in OCT (the third use case), VTT completed the fabrication of multiple test chips containing MMIs, ADCs, MZIs and full PDR structures, and delivered them to Gooch&Housego Ltd. (G&H) for characterisation. Initial tests confirmed that key passive components meet or exceed target specifications, including >100 nm bandwidth and polarisation extinction ratios above 15 dB.

Integration and early validation in three use cases
All use cases underwent preparation and early validation of the first-generation devices, including optical characterisation, calibration of measurement setups and initial benchmarking of key performance parameters. These activities confirmed component-level functionality and established reliable procedures for the subsequent system-level validation phase.

In the first use case, OMMA carried out comprehensive optoelectronic characterisation of the first-generation graphene-on-Si photodetector chips (Figure 4). Using a 1550 nm laser source and an edge-coupling setup, photocurrents of 0.5–7.5 mA at 10 V bias were measured, with responsivity values up to 0.4 A/W. These results validate the expected behaviour of the devices and provide a performance baseline for integration into the LiDAR receiver system.

Linköping University (LIU), in the second use case, adapted and calibrated the gas-mixing system using a reference gas chromatograph to ensure accurate evaluation of gases of

GRAPHENE FLAGSHIP ANNUAL REPORT 2025

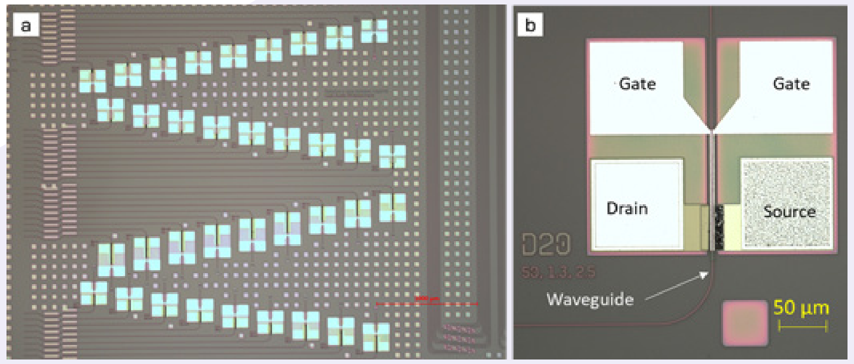

Figure 5. Optical microscope image of completed photo detectors for use case 2. a) Group of PDs where length, WG width and distance to source and drain has been varied. b) Close-up of one single PD. Credit: Silex Microsystems

Figure 7. Ioanna Zergioti, Next-2Digits talk about project progress at Graphene Week. Credit: Marco Messina
Figure 8. Katerina Magoula presenting at Nanotexnology. Credit: Next-2Digits

interest. Inside the calibrated regime, LIU initiated laboratory testing with varying CH_4 concentrations, observing expected sensor responses together with humidity-related interferences. In parallel, Senseair AB (SENSE) performed initial inspection and SEM analysis of the prototypes. While challenges were identified, particularly in suspended waveguide structures, the team defined a revised fabrication approach aimed at improving yield and robustness (Figure 5). Preparations for extended gas-testing at LIU are ongoing.

In use case 3, G&H tested first-generation chips provided by VTT, selecting specialist fibre optics that achieved coupling losses close to the required specifications. Sub-component measurements confirmed that polarisation extinction ratio (PER) and common-mode rejection ratio (CMRR) met or exceeded target levels. In joint work, G&H and VTT characterised the first PDR test chips using ultra-high numerical aperture (UHNA) fibre, further reducing fibre-to-chip coupling losses. Component-level evaluation showed CMRR values above 30 dB in many configurations, demonstrating the viability of the integrated PDR architecture for OCT imaging.

DISSEMINATION AND EXPLOITATION

In 2025, Next-2Digits continued to actively disseminate its results and exploitable foreground, strengthening engagement with the European 2D materials community and extending outreach to the public through established communication channels. The project website (www.next-2digits.eu) and LinkedIn account (www.linkedin.com/company/next-2digits) remained central platforms for sharing updates, goals and impact, complemented by contributions to the Graphene Flagship network and YouTube content. Regular updates and press releases ensured visibility and transparency, while promotional materials such as flyers and roll-ups supported participation at major events.

Throughout the year, the project participated in six international conferences, presenting key achievements through oral talks, posters, and scientific publications. A highlight was the project's strong presence at Graphene Week (Figure 6), where partners delivered several presentations and hosted a dedicated parallel session on Electronics, Photonics and Optoelectronics (see Figure 7). These activities strengthened collaboration within the Graphene Flagship ecosystem and positioned Next-2Digits as a leading contributor to photonic and optoelectronic integration using 2D materials.

Notable external engagements included SPIE Photonics West 2025, where NTUA showcased advances in laser-induced transfer for plasmonic structures, and Nanotexnology 2025 (Figure 8), Europe's largest networking event in nanotechnologies and printed electronics, where we presented results on advanced photodetectors and modulators enabled by LIFT-based 2D material integration, and Optical profilometry for 3D mapping of photonic integrated circuits. These efforts underline the project's commitment to knowledge sharing and its role in shaping next-generation photonic technologies.

POWERED BY THE GRAPHENE FLAGSHIP

Being part of the Graphene Flagship directly supports Next-2Digits in reaching its technical and scientific goals. Access to the initiative's research network and expert community has already enabled collaboration on several joint publications, helping to validate the project's results and strengthen the scientific foundation of its integration methods. Through shared knowledge, coordinated research activities and visibility at Graphene Flagship events, the project has been able to accelerate its progress in wafer-scale 2D-material integration and photonic device development. This collaboration ensures that Next-2Digits' advances contribute to, and benefit from, the wider European effort to industrialise graphene and 2D material technologies. The consortium is also actively engaged in the Graphene Flagship community each year, regularly contributing to its activities and maintaining a strong presence at Graphene Week, where partners showcase project outcomes and exchange insights with the wider European 2DM community.

ON THE HORIZON

As Next-2Digits enters its final year, the focus shifts from first-generation prototypes to completing fabrication runs, refining material integration and preparing the demonstrators for system-level validation. Focusing on wafer-scale transfers, initial PICs and device benchmarks now established, the next period will concentrate on maturing the technologies for testing in realistic environments across LiDAR, gas sensing and OCT imaging.

Figure 6. Next-2Digits partners at Graphene Week 2025. Credit: Giò Tarantini/Gruppo Tonello

NTUA will continue studying how multilayer graphene influences photodetector photo-response and will enhance the modulator stack by adding Al_2O_3, with VTT evaluating the performance of the updated devices. To improve the imaging of the laser set-up and the resulting quality and line-edge roughness of the transferred pixels, NTUA will employ a digital micro-mirror device as a substitute for a mask.

Fabrication will advance to the second run across all applications. OMMA will finalise the LiDAR Run-2 design based on characterisation feedback, targeting higher responsivity and integration into a coherent FMCW array. For greenhouse-gas sensing, Silex will implement the revised process flow to realise functional suspended waveguides and graphene detectors, aiming to deliver testable prototypes by mid-2026. For OCT imaging, VTT will integrate graphene photodiodes into PDR chips and refine PBS designs to improve polarisation extinction and bandwidth. Key challenges during these activities include preserving graphene quality in back-end processing, achieving high-yield suspended structures, and ensuring compatibility between passive photonics and active graphene devices.

Validation efforts will intensify in parallel. G&H will continue testing PDR devices, improve the test setup for more complete analysis, and conduct packaging evaluations; upcoming VTT chips with graphene PDs will enable direct optical-versus-electrical comparisons. OMMA will progress LiDAR receiver integration and assemble a ground-test prototype. For gas sensing, SENSE will begin photonic and gas-response testing once revised chips are delivered, with LIU supporting environmental validation; LIU will also complete sensor calibration (including algorithms to compensate CH_4 cross-effects), fabricate and validate systems for field use and carry out field measurements in biogas facilities with Bert.

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2. Nat Commun 16, 1417 (2025), https://www.nature.com/articles/s41467-025-56357-0

Electronics and Photonics

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2D PILOT LINE

Driving wafer-scale 2D integration and collaborative innovation

> The 2D Pilot Line has made significant advances in wafer-scale growth, transfer and encapsulation of 2D materials this year, bringing graphene and TMDCs closer to integration into industry-standard semiconductor processes."

Inge Asselberghs
Project Coordinator
imec

THE 2D PILOT LINE (2D-PL) is advancing Europe's semiconductor innovation by accelerating the integration of two-dimensional (2D) materials into photonic and electronic technologies. This four-year initiative provides end-to-end prototyping services to integrate graphene and transition-metal dichalcogenides (TMDCs) with established silicon-based platforms. By developing and validating processes in a fabrication relevant environment, the project aims to bring 2D material technologies closer to industrial production and support organisations across Europe, including research institutes, start-ups, SMEs, large companies, integrated device manufacturers and semiconductor foundries in the development of state-of-the-art integration methods.

A central feature of the 2D-PL is its multi-project wafer (MPW) service, which enables multiple users to test their designs on shared wafer runs. This approach reduces costs and shortens development cycles while giving industry and researchers access to advanced graphene- and TMDC-based photonic and electronic device technologies in development.

PROGRESS IN 2025

During the past year, the 2D-PL made significant progress toward enabling the industrial integration of 2D materials in semiconductor technologies. Key advances were achieved in the growth, transfer and encapsulation of graphene and transition-metal dichalcogenides, alongside the development of fabrication processes compatible with large-scale semiconductor manufacturing. The project also initiated pilot fabrication activities, including MPW runs and early process design kits (PDKs) to support device development. In parallel, partners established common characterisation protocols and wafer-scale metrology approaches to ensure consistent quality and performance across the 2D-PL, strengthening collaboration across the European 2D materials ecosystem.

Process modules for graphene integration

Over the past year, work package one advanced key process modules for the growth, transfer and encapsulation of graphene to support its large-scale integration in electronics, photonics and sensing technologies. Progress included the development of new graphene growth templates and improvements in bonding and debonding modules through the testing of new adhesives. The team also developed improved dielectric stacks for graphene encapsulation, including active dielectric materials with low equivalent oxide thickness (EOT). In addition, new graphene interface cleaning processes were tested to improve material quality. Throughout the year, work package one ensured the continuous supply of graphene wafers to other work packages, supporting activities in photonics, electronics, characterisation and metrology.

Process modules for TMDC integration

Work package two made significant progress in developing tools, materials and process modules for the growth, transfer and encapsulation of transition metal dichalcogenides (TMDCs). A key focus was the development and upgrade of a 300 mm growth tool to enable the deposition of MoS_2 on large sapphire substrates. The team explored a wide range of process conditions and upgraded hardware to expand process compatibility, improve 2D layer performance and increase growth efficiency and safety. In parallel, progress was made in transfer processes, particularly debonding methods and the development of alternative polymers. Encapsulation work on 200 mm wafers led to the development of a PEALD AlON thin interlayer on MoS_2, enabling subsequent deposition of closed Al_2O_3 layers with competitive equivalent oxide thickness and threshold voltage tuning.

2D for photonic applications

In 2025, work package three worked to advance light-based chip technologies by integrating graphene into existing silicon manufacturing lines at IHP and VTT. Teams across partner sites carried out modelling and simulation of device designs and used these results to begin fabricating passive and active graphene photonic circuits on pilot wafers. The work also supports the development of shared MPW runs and the creation of practical design toolkits, enabling other partners to design devices that incorporate graphene-based photonic components.

2D for electronic and sensing applications

Work package four made important progress toward the large-scale integration of 2D materials – including graphene, MoS_2 and WS_2 – for future electronics and sensing technologies. A key milestone was the successful launch of two graphene MPW runs. The team also advanced the scaling of fabrication processes toward industry-standard 300 mm wafers, improved contact technologies and began developing residue-free lithography processes tailored for 2D materials. In addition, more uniform testing routines were introduced across partner sites, and initial process design kits (PDKs) were developed and implemented in ongoing MPW runs.

The 2D-PL team at Graphene Week 2025. Credit: Giò Tarantini/ Gruppo Tonello

Characterisation and metrology

In the past year, work package five focused on developing characterisation protocols, metrology tools and standardisation approaches for 2D materials. Major achievements during the first year included the definition of common characterisation protocols for all pilot line sites, enabling consistent quality control and benchmarking of key performance indicators for 2D materials and devices. The team also demonstrated fast Raman and photoluminescence mapping on 300 mm wafers and conducted a survey of existing standards and ongoing standardisation activities relevant to the pilot line.

Pilot Line operation and access

Work package six focused on providing access to the pilot line through service offerings centred on MPW runs. A dedicated support programme was introduced to offer reduced fees to selected customers who provide feedback on the MPW process, the use of process design kits (PDKs) and the technical results generated. To support adoption, the project organised hands-on PDK training at imec in September 2025, covering the KLayout-based design environment used for MPW runs offered by GSEMI and AMO. IHP leveraged the KLayout potential by adding Python packages for graphene-based photonic device design; on the other hand, VTT guided attendees on Cadence towards graphene-based sonsor design with CMOS readout. The pilot line's activities were also showcased at major industry events, helping strengthen engagement with the wider semiconductor ecosystem. At the 2D-PL booth at SEMICON Europa, Executive Director of the European Union's Chips Joint Undertaking and former director of the Graphene Flagship Jari Kinaret and Frank Holsteyns, VP R&D Unit Process & Modules at imec, steering group leader for technology development of the NanoIC project, met with Inge Asselberghs, strategic development director at imec and coordinator of the 2D-PL and NanoIC project, to discuss synergies between the project and the Chips JU pilot lines.

Project management and coordination

The goal of work package seven is to coordinate the activities of the 2D-PL, ensuring efficient project management, overseeing common initiatives within the Graphene Flagship and maintaining connections with external stakeholders, including the European Commission. Over the past year, the work package organised a joint consortium and General Assembly meeting at IHP in Frankfurt am der Oder in May 2025, bringing partners together to share progress, plan future activities and strengthen collaboration across work packages. The team also coordinated the month 12 review in December, which received positive feedback. In addition, work package seven ensured alignment and active participation in key Graphene Flagship activities, including the Science and Technology Forum and various working group meetings.

DISSEMINATION AND EXPLOITATION

Over the past year, dissemination activities focused on introducing the 2D-PL and promoting the first MPW runs, which were publicised through the Graphene Flagship website, newsletters, social media and EUROPRACTICE channels.

Engagement with the research and industrial community was supported through a range of events and workshops. The ongoing digital workshop series "Pioneering 2D Materials for Semiconductor Industry" continued to provide updates on project progress and promoting MPW opportunities. Events covered topics such as characterisation methods and biosensor applications, attracting over 100 participants each. The project also organised and contributed to a scientific workshop and a session in the Innovation forum at Graphene Week 2025, engaging the wider graphene community. Exhibition activities included a dedicated display at Graphene Week 2025 showcasing the pilot line processes and devices. This exhibition was then adapted for the SEMICON Europa industry fair.

Exploitation and business development activities were guided by a dynamic business plan and market analysis examining the potential of 2D materials in sensors, electronics and photonics. Partners actively engaged industrial stakeholders to encourage participation in MPW runs. Outreach also included collaboration with organisations such as the Swedish Innovation Programme for Graphene and the Swedish Chip

Top. Project Coordinator Inge Asselberghs presents the 2D-PL in a Graphene Week Innovation Forum session. Credit: Giò Tarantini/ Gruppo Tonello
Bottom. The 2D-PL provided hands-on instruction on the use of process design kits at a training at imec. Credit: Chiara Mancini

A panel discussion during the 2D-PL session at Graphene Week in Vicenza, Italy. Credit: Giò Tarantini/ Gruppo Tonello

DID YOU KNOW?
The 2D-PL offers a 50% reduction in fees for MPW run customers who are willing to give its pilot line hosts feedback on the received devices through its support programme.

Competence Centre. Early discussions with industrial partners have addressed topics such as intellectual property, competitive positioning and future commercial opportunities, laying the groundwork for long-term exploitation of the pilot line's technologies and services.

POWERED BY THE GRAPHENE FLAGSHIP

The Graphene Flagship ecosystem provides valuable synergies and collaboration opportunities for the 2D-PL. The project also benefits from the Graphene Flagship's established communication channels, which help amplify its visibility and outreach. For example, videos recorded at Graphene Week have played an important role in promoting the project and its multi-project wafer (MPW) runs.

Collaboration with related projects has also enabled knowledge exchange and joint dissemination activities. The 2D-PL worked with the 2D Engine project on a workshop on characterisation methods in February and co-organised an in-person workshop at Graphene Week with the GATEPOST and 2DNEURALVISION projects. Participation in the Graphene Flagship's standardisation committee further enables the 2D-PL to contribute to shaping future standards for 2D materials within the IEC and ISO standardisation bodies.

ON THE HORIZON

Over the coming year, the 2D-PL will focus on further advancing the industrial integration of 2D materials into semiconductor manufacturing processes. Key technical priorities include improving the growth, transfer and encapsulation of graphene and transition metal dichalcogenides, while scaling fabrication processes toward larger wafer sizes. Work will continue to ramp up MoS_2 deposition following recent equipment upgrades and to support the integration of materials such as MoS_2 and WS_2 on wafers of up to 200 mm. At the same time, partners will further develop electronic and photonic platforms and process design kits to enable reliable, repeatable MPW runs and support wider adoption of graphene-based photonic and electronic devices.

Several challenges remain as the project moves toward greater industrial readiness. Ensuring wafer homogeneity, repeatability and higher device yields will be essential for large-scale manufacturing. Continued progress is also needed in interface cleanliness, transfer processes and the reliability of 2D-material-based components. To support this, the project will further validate common characterisation protocols, advance wafer-scale metrology tools and test new techniques such as scanning nitrogen-vacancy microscopy. Alongside technical development, the 2D-PL will continue expanding its user base by onboarding new customers for MPW runs, enhancing design tools and training and strengthening engagement with industry through innovation forums and collaboration with its Industrial Advisory Board.

The 2D-PL welcomed Executive Director of the European Union's Chips Joint Undertaking and former director of the Graphene Flagship Jari Kinaret and Frank Holsteyns, VP R&D Unit Process & Modules at imec, at the 2D-PL booth at SEMICON Europa. Credit: Rebecca Waters

Electronics and Photonics

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2D PILOT LINE
FROM THE GRAPHENE FLAGSHIP

Explore
the 2D Pilot Line value chain

In 2025 2D-PL presented its work on integrating two-dimensional materials in semiconductor technologies at SEMICON Europa and Graphene Week. The Graphene Flagship project is accelerating the transition of 2DM from lab-scale research toward real industrial integration in photonics and electronics. Photos by Giò Tarantini/ Gruppo Tonello and Rebecca Waters

ARMS

Graphene-powered supercapacitors for a sustainable future

THE ARMS PROJECT is driving a breakthrough in sustainable energy storage by developing next-generation supercapacitors that combine high performance with eco-friendly design. Our goal is to create devices with energy densities exceeding 50 Wh/kg – comparable to traditional batteries – while preserving the fast charging, long lifespan and safety that supercapacitors are known for. Using advanced materials, such as graphene-rich, bio-based carbon and innovative manufacturing techniques such as atomic layer deposition (ALD), ARMS is building a new European value chain for clean energy technologies. To showcase real-world impact, we are developing two demonstrators: a wireless sensor powered by a printed flexible supercapacitor and a drone where structural supercapacitors serve as both the power source and part of the airframe. Through collaboration among research institutions and industry partners, ARMS aims to deliver affordable, scalable solutions for applications ranging from consumer electronics to electric vehicles – all while prioritising non-toxic materials and processes for a greener future.

> Our innovations in materials, processes and sustainable design are setting new benchmarks for supercapacitors.”

Matti Mäntysalo
Project Coordinator
Tampere University

PROGRESS IN 2025

Throughout 2025, the ARMS project advanced its mission to develop next generation, sustainable supercapacitor technologies by making coordinated progress across all work packages. The project brings together materials science, electrochemistry, device engineering and sustainability assessment to create a fully integrated innovation pipeline – from biomass-derived electrode materials to scalable device prototypes. Each work package builds on the achievements of the others, ensuring that developments in raw materials, fabrication methods, performance enhancement and electrolyte chemistry converge into practical, high performance energy-storage solutions.

ARMS partners made substantial progress in understanding and optimising every layer of the supercapacitor system. New bio-derived carbons with exceptional performance were synthesised and characterised; advanced electrode manufacturing routes were established for both flexible and structural devices; and atomic layer deposition techniques were refined to significantly enhance capacitance without compromising conductivity. In parallel, novel water-based hybrid electrolytes were developed to enable safer, environmentally friendly and fluorine free operation at higher voltages. These material and process innovations were then integrated into functional cells and demonstrator devices, including flexible sensors and structural composites, showcasing ARMS technology in real applications. Complementary efforts in sustainability assessment, dissemination and project coordination ensured that ARMS advances are not only innovative but also responsible, visible and well supported across the consortium.

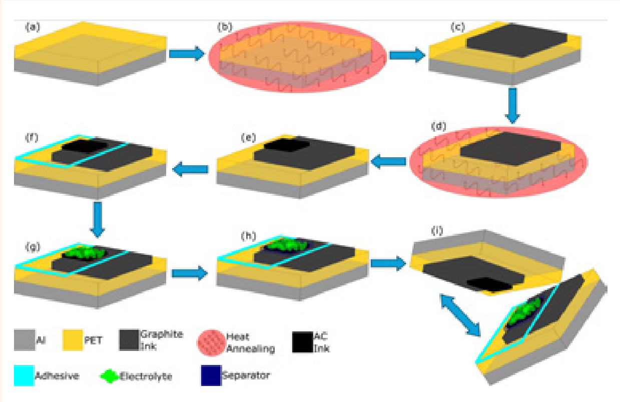

Figure 1. Supercapacitor fabrication steps. (a) Al/PET substrate. (b) Pre-heating of the substrate. (c) Deposition of graphite ink on the PET side. (d) Drying of the graphite ink. (e) Deposition of AC ink to form the electrode layer. (f) Application of adhesive onto the PET and part of the current collector layer. (g) Addition of aqueous electrolyte onto the electrode layer. (h) Placement of a cellulose paper separator onto the electrode. (i) Assembly and sealing of the two electrodes face to face.

Synthesis of raw graphene-containing carbon-based electrode materials

In 2025, the ARMS project made major progress in identifying high performance, bio-derived carbon materials for next-generation supercapacitors. Among the different biomass sources explored, carbon produced from alder wood showed exceptional promise. It achieved an extremely high surface area of 2844 m^2/g and a specific capacitance of 265 F/g – more than twice that of commercial reference materials. Carbons made out of pistachio shells also demonstrated strong and reliable performance, regularly exceeding 200 F/g.

Alongside material discovery, the team deepened its understanding of how pore structure and internal architecture influence the energy storage capabilities of carbon electrodes. This knowledge now guides ongoing optimisation steps to further improve capacitance and overall energy density.

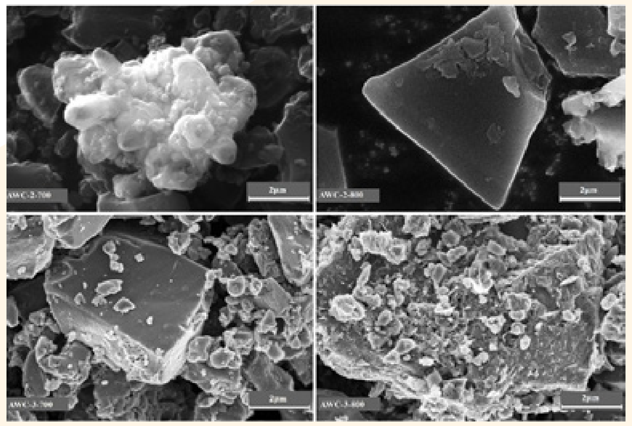

Figure 2. Scanning Electron Microscope (SEM) images of activated wood carbon (AVC).

Electrode fabrication

Work package two focused on turning the bio-derived carbon materials into practical, high-quality electrodes suitable for both flexible and structural supercapacitor devices. To achieve this, the team developed a set of complementary fabrication techniques – including direct ink writing, doctor blading, dip coating and roll-to-roll printing – to process graphene-rich carbon inks onto a variety of substrates.

For flexible devices, printing methods were refined to create uniform, high-performance electrode layers. For structural supercapacitors, specialised processes were developed to deposit graphene, MXene and composite materials directly onto carbon fibres. All electrode types demonstrated excellent thermal stability, enabling further enhancement by atomic layer deposition (ALD).

A key highlight of the year was the fabrication of graphene-enhanced structural electrodes that achieved specific capacitances above 15 F/g – over 50 times higher than those of original carbon fibres – marking a significant step forward for multifunctional energy-storing composites.

Electrode booster (ALD)

In 2025, work package three explored how atomic layer deposition (ALD) could improve the performance of activated carbon electrodes. ALD applies ultra-thin coatings one atomic layer at a time, giving precise control over the surface chemistry. Titanium oxide (TiO_2) was deposited onto carbon electrodes because of its ability to store charge through surface-based redox reactions.

After extensive testing, the optimal coating thickness was determined to be a 2.3-nanometre TiO_2 layer formed using 60 ALD cycles. At the single-electrode level, the nanostructured coating achieved a capacitance increase of more than 60% without significantly increasing resistance – an ideal combination for high power devices. The improved performance was shown to come primarily from enhanced redox activity at the electrode surface.

In a move toward sustainability, the team used simple saltwater (NaCl solution) instead of organic electrolytes, demonstrating that high performance can be achieved with environmentally friendly materials. The work package also outlined how roll-to-roll ALD systems could make this approach fully scalable for low-cost, eco-friendly manufacturing.

A detailed description of this work can be found in Vitto et al., J. Power Sources, 662 (2026), 238691, https://doi.org/10.1016/j.jpowsour.2025.238691.

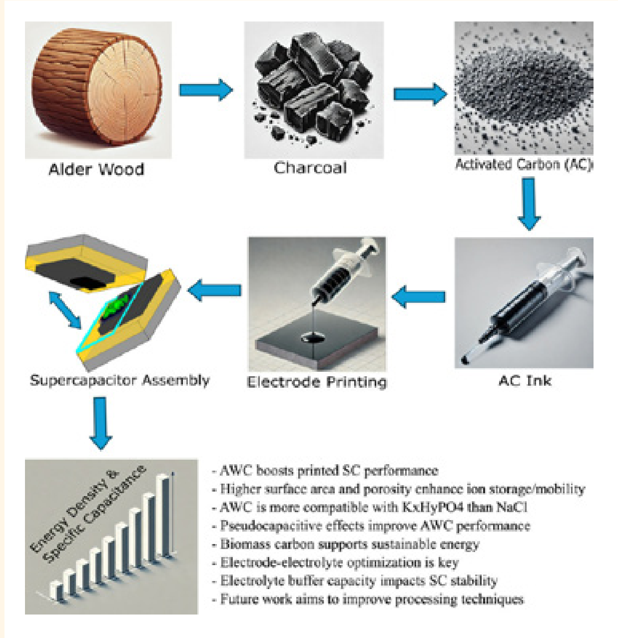

Figure 3. Graphical abstract of the scientific publication “Enhancing specific capacitance and energy density in printed supercapacitors: The role of activated wood carbon and electrolyte dynamics” in Carbon Trends, Volume 18 (2025), 100436.

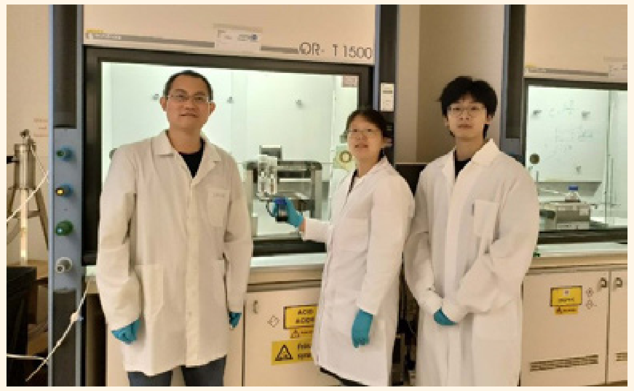

Figure 4. Work package two team from KTH Royal Institute of Technology. Credit: ARMS

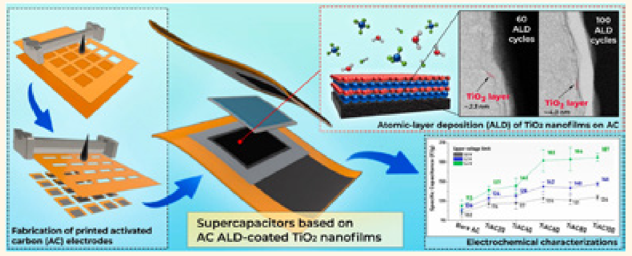

Figure 5. Graphical abstract of the scientific publication “Interfacial engineering of conformal titanium oxide nanofilms on porous carbon supercapacitor electrodes via atomic layer deposition” in Journal of Power Sources, Volume 662 (2026),238691.

GRAPHENE FLAGSHIP ANNUAL REPORT 2025

Electrolytes
A distinguishing feature of ARMS is its focus on safer and more environmentally friendly electrolyte formulations. Work package four is developing advanced water-based "hybrid" electrolytes that use only minimal amounts of organic solvent. This approach enables higher operating voltages than conventional aqueous electrolytes, while offering better compatibility with the carbon materials developed for the project.

The resulting electrolytes are non-flammable, significantly less toxic than commonly used alternatives and suitable for more cost-efficient manufacturing, because the constituents are more abundant and can be manufactured at a lower cost, and most importantly, they eliminate the need for lengthy drying steps during cell manufacturing.

So far, work package four has produced a fluorine-free electrolyte capable of stable cycling at 2.3 V, delivering excellent performance with ARMS carbon electrodes. The team is also investigating the fundamental interactions between electrode materials and electrolytes and has supported the other work packages with electrolyte formulations suitable for the systematic characterisation of electrode materials across various laboratory setups.

Supercapacitor device integration and demonstration
Work package five bridges the gap between material development and real-world applications. Using the electrodes, electrolytes and coatings produced in earlier work packages, the team assembled several types of devices: laboratory-scale test cells, pilot-scale pouch cells and structural supercapacitor composites.

Lab-scale devices enabled optimisation of electrode architecture and electrolyte utilisation. Roll-to-roll compatible electrodes were then integrated into asymmetric pouch cells with enhanced energy density. In parallel, structural supercapacitor laminates were produced, combining mechanical strength with energy storage functionality.

To demonstrate the practical value of ARMS technology, two application cases are being developed: battery-free wireless environmental sensors powered solely by flexible supercapacitors, and drone components that use structural supercapacitors that provide both energy storage and load-bearing functionality.

These demonstrations confirm that ARMS innovations can be integrated into real devices, opening the door to lightweight, sustainable energy-storage solutions.

Sustainability assessment
In 2025, work package six advanced the sustainability foundations of the ARMS project by developing a dedicated Safe-and-Sustainable-by-Design (SSbD) framework tailored for next-generation supercapacitors. This framework brings together safety, environmental and circularity indicators to guide materials and process development from an early stage. The first major milestone – the SSbD framework report – was completed during the year, and initial hazard and exposure assessments for key chemicals used in ARMS technologies were carried out using established tools such as VEGA, INTEGRA and Danish QSAR.

Building on this groundwork, work package six began preparing a prospective life cycle assessment (LCA) of ARMS supercapacitor production and its comparison with commercial alternatives. Work is now underway to gather life cycle data, set up model structures using open source LCA tools, and collaborate

Figure 6. AIMEN Technology Center team working in work packages two and four. Credit: ARMS

Figure 7. Work package six team from the University of Southern Denmark developing SSbD framework in ARMS. Credit: ARMS

closely with other work packages to ensure accurate and comprehensive sustainability insights. Through this approach, the work package ensures that sustainability remains integrated into every step of ARMS development.

Dissemination, exploitation and communication
Work package seven ensured that the achievements of ARMS reached both scientific and general audiences through a varied and well-coordinated communication strategy. A unique visual identity created at the outset of the project was actively used to support clear, consistent outreach.

Throughout the year, the project actively used social media, with dedicated LinkedIn and X accounts sharing updates, results and partner stories. By the end of 2025, the LinkedIn page had grown to over 550 followers, and four project newsletters had been published. The project website hosts news, event updates and contributions from consortium members, further increasing visibility.

Figure 8. ARMS consortium partners at the University of Southern Denmark, Odense, October 23–24, 2025. Credit: ARMS

Consortium partners presented at international conferences and produced three peer-reviewed publications. Strong ties with the wider Graphene Flagship community were maintained through participation in flagship meetings and working groups, helping maximise knowledge exchange and impact.

Figure 9. ARMS representatives Hamed Pourkheirollah and Jinhua Sun at the ARMS stand during Graphene Week 2025. Credit: ARMS

Project management and coordination
All management activities progressed according to plan, ensuring smooth coordination across the consortium. A key highlight of 2025 was the in-person consortium meeting held in Denmark on 23–24 October. This event brought together partners from across Europe, allowing in-depth discussions, progress updates, and collaborative planning for the next phase of the project. The meeting was hosted by the project's Danish partners – University of Southern Denmark and InnoCell ApS. The meeting strengthened partnerships and confirmed priorities for the coming year.

As the project moves forward, work package eight will continue to foster regular communication, follow up on agreed actions, and prepare for the next consortium gathering. Maintaining strong collaboration with stakeholders will also be key, and the team will make sure all upcoming management tasks are handled effectively. Strong and steady coordination remains central to keeping the project aligned and effective.

DISSEMINATION AND EXPLOITATION

In 2025, Project ARMS built strong visibility across scientific, industrial and Graphene Flagship fora. The year opened with ARMS's first peer-reviewed article on activated wood carbon for printed supercapacitors, establishing early scientific traction and credibility (3 January 2025). Industry engagement scaled up in March at JEC World 2025, where our partner, AIMEN Technology Center, showcased ARMS results in structural supercapacitors and advanced composites to a large professional audience, broadening links with potential adopters and suppliers. ARMS researchers then connected with the international carbon materials community at Carbon 2025 (Saint Malo), presenting advances in activated carbon for energy storage and fostering collaborations with global experts. A Graphene Flagship highlight was Graphene Week 2025 – with a project booth, a presentation at the annual meeting, participation in the Project Managers Network and a podcast appearance – cementing ARMS's visibility within the Graphene Flagship ecosystem and the 2D materials community. Consortium-level engagement continued at the 5th ARMS Consortium Meeting (Denmark), where partners publicly reported work package progress and aligned on next step collaborations with the Graphene Flagship, strengthening both internal knowledge exchange and outward messaging.

PARTNER STORIES, OUTREACH, AND MEASURABLE COMMUNICATION PROGRESS

Beyond events, ARMS used its website to publish partner contribution stories that explain how specific WPs and organisations drive results – most notably Beneq's December feature on scaling ALD from laboratory tools to industrial platforms (P series, SCS 1000, Genesis roll-to-roll), underscoring exploitation pathways toward manufacturing. Public-facing communication also highlighted people and processes: the Beyond the Lab Coat interviews humanised the project and helped broaden its audience beyond technical stakeholders. Complementing the website, ARMS maintained an active presence on LinkedIn – sharing meaningful updates (including a 2025 activity roundup and Graphene Week highlights) to steadily grow its follower base and reach, thereby meeting its dissemination goals for community building across Europe's innovation ecosystem.

Figure 10. Interview series "Beyond the Lab Coat" on the ARMS project website. Credit: ARMS

POWERED BY THE GRAPHENE FLAGSHIP

Being part of the Graphene Flagship has been a significant asset for the ARMS project, providing strong support in advancing its scientific and technological ambitions. The initiative's collaborative ecosystem offers access to a uniquely coordinated network of expertise, structured governance and harmonised activities in standardisation, innovation and technology development. This integrated environment directly contributes to ARMS' progress in developing graphene-rich, bio-based carbon materials and graphene-decorated carbon fibres for next-generation, eco-friendly supercapacitors.

In 2025, ARMS further deepened its engagement with the community by actively participating in Graphene Week 2025, one of the Graphene Flagship's most influential annual events. This participation enabled the project to present its latest achievements, exchange insights with leading European researchers and ensure its scientific outputs remain aligned with emerging trends in graphene research and advanced manufacturing.

Membership in the Graphene Flagship not only accelerates ARMS' R&D efforts through continuous knowledge exchange but also strategically positions the project within a broader European innovation landscape. This strengthens ARMS' visibility, fosters collaboration and supports the long-term impact of its technological developments.

Figure 11. ARMS representatives at the Graphene Week 2025. Credit: ARMS

ON THE HORIZON

In 2026, ARMS will take decisive steps to show that our vision is not just possible – it will be viable. Our focus will shift toward integrating supercapacitor devices into real-world applications and demonstrating their feasibility. These efforts will mark a critical milestone in transforming advanced materials and sustainable design into tangible solutions for next-generation energy storage.

In 2026, ARMS will move from proof-of-concept to proof-of-viability. We will integrate our best performing materials and processes into application driven demonstrators: battery-free wireless environmental sensors powered by printed flexible supercapacitors and structural supercapacitor components that both store energy and carry load in a drone airframe – clear tests of real world feasibility and added value. In parallel, we will mature hybrid, fluorine-free aqueous electrolytes operating up to 2.3 V, and advance roll-to-roll compatible ALD routes that have already delivered strong performance gains at lab scale. These steps – combined with our Safe-and-Sustainable-by-Design (SSbD) framework and an ongoing prospective LCA – are aimed at demonstrating not only that ARMS devices work, but that they can be manufactured, adopted and sustained responsibly in real products.

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SURPRISE ME

Salt water + 2.3 nm ALD coating = >60% capacitance increase (single-electrode level). One of the year's most surprising findings was that an ultrathin (≈2.3 nm) TiO_2 film grown by ALD on porous carbon boosted single-electrode capacitance by over 60% (up to 65%) without introducing meaningful additional resistance. Notably, this enhancement was achieved in a simple NaCl "salt water" electrolyte rather than an organic solvent – and it did so in a simple NaCl "saltwater" electrolyte rather than an organic solvent. This result upends the common trade-off between power and energy in eco-friendly systems and points to a practical path where greener electrolytes and scalable surface engineering can deliver high performance together. It also validates our scale up focus on roll-to-roll ALD, with direct implications for manufacturability and cost.

Energy

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University of Southern Denmark, Denmark
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PARTNERING PROJECTS
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VEGA
SOLiD

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SOLVIONIC
Istituto Nazionale di Ricerca Metrologica
University of Torino
Jozef Stefan Institute
GREMI CNRS – University of Orleans
AVESTA Battery and Energy Engineering
Aalto University
Centre National de la Recherche Scientifque – CNRS
Ocsial Europe SARL
Armor Battery Films SA
Coatema Coating Machinery GmbH
Tomas Bata University in Zlin
Bern University of Applied Sciences

ARMS
Supercapacitors: Energize your world

GRAPHERGIA

Sustainable laser-assisted graphene manufacturing for smart clothing and Li-ion batteries

GRAPHERGIA IS a three-and-a-half-year research and innovation project, running since October 2023, funded by the European Union (EU) under the Graphene Flagship initiative. It brings together 11 industrial, academic and SME partners across six EU countries to develop and pilot a novel solution to revolutionise the field of energy harvesting and storage through innovative applications of graphene. GRAPHERGIA aims to unlock the potential of laser-assisted graphene production to shape the future of innovative textile applications and next-generation Li-ion batteries. Working across research and industry, GRAPHERGIA is piloting these solutions with a focus on sustainability, safety, and real-world manufacturability to help accelerate market uptake.

PROGRESS IN 2025

This second project year focused on three key areas: (i) optimising laser-assisted graphene materials for conductive functional textiles and Li-ion batteries; (ii) advancing micro-flexible supercapacitors via novel gel electrolytes; and (iii) developing scalable methods for large-area deposition of energy-harvesting layers together with integrated power-management electronics that interface the e-textile with the external environment. These research efforts were undertaken collaboratively across the consortium and have yielded several publications in peer-reviewed journals and conference proceedings. This body of work also lays the foundation for three demonstration cases planned from 2026 onward. In parallel, the GRAPHERGIA team advanced the sustainability dimension through a Life Cycle Sustainability Assessment (LCSA) and implemented an impact strategy encompassing communication, dissemination and exploitation.

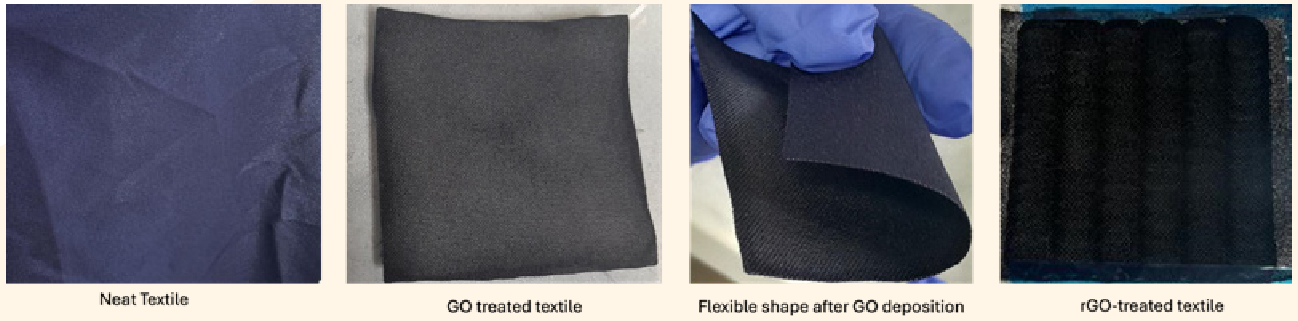
Scientific coordination and project management

Work package one, led by the Foundation for Research and Technology – Hellas (FORTH), continued to ensure effective project governance, coordination and data management. The project steering committee, comprising all work package leaders, convened every two months to monitor the progress of the project and ensure synchronisation of subsequent steps across ongoing tasks. Additionally, the consortium met in person at the general assembly, held in May 2025 at the University of Gustave Eiffel (UGE)/ESYCOM lab in Paris, France. In November 2025, the consortium held its first meeting with the Industrial Reference Group, comprising experts in graphene production, metrology, standardisation and electrochemistry. This group will accompany GRAPHERGIA throughout the project, advising on product validation, market trends and priority setting.

GRAPHERGIA has been a strong team effort from the outset, delivering advances across the value chain. With SME support, our materials partners matured laser-assisted graphene for smart textiles and Li-ion batteries, advanced gel electrolytes for micro-flexible supercapacitors and developed energy-harvesting layers with integrated power-management electronics. In parallel, the life cycle assessment, Safe-and-Sustainable-by-Design (SSbD) and exploitation teams translated these outputs into scalable, greener pathways. Targeted and professional communication and dissemination further amplified our project's impact."

Spyros Yannopoulos
Project Coordinator
University of Patras and Foundation for Research and Technology – Hellas

GRAPHERGIA team at the Consortium Meeting in Paris.
Credit: GRAPHERGIA



Process steps of the Reduced Graphene Oxide (rGO) treated textile. Credit: ADAMANT

Design, development, and optimisation of textile-based TENGs and micro-flexible SCs

This year, work package two, led by the coordination team at FORTH, focused on optimising laser-assisted production of graphene-based materials on textiles and other flexible substrates. We developed two scalable, pilot-scale-ready laser processes for coating graphene onto textiles and heat-sensitive substrates, using sources capable of converting a range of precursors. In parallel, we established a binder-free LIB anode route via *in situ* laser-induced decomposition of suitable precursors directly on Cu current collectors.

This research enabled versatile substrate adaptation, in which optimised laser parameters produced uniform laser-reduced graphene oxide (LrGO) coatings on polyester, polyamide, technical fabrics and paper without causing substrate damage. By fine-tuning graphene oxide (GO) loading and laser energy during ambient laser reduction of polyester, we achieved exceptionally low sheet resistance. This process has been successfully transferred from the benchtop to the pilot roll-to-roll line, enabling meter-scale production of graphene-coated textiles with consistent electrical and morphological properties, demonstrating industrial viability.

Overall, the entire workflow relies on water-based GO, avoids toxic chemicals and operates under localised, energy-efficient laser irradiation, fully aligning with Sustainable-by-Design (SSbD) principles.

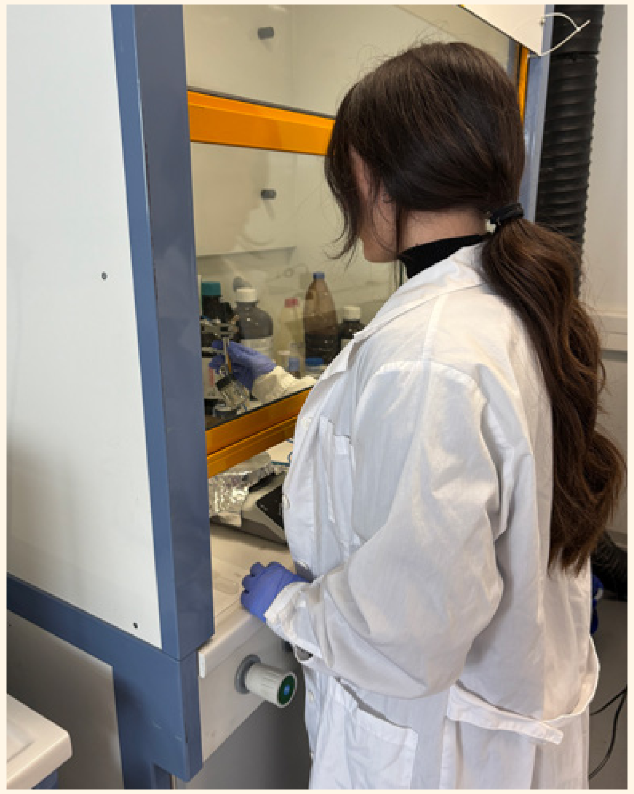
The partners presented research work primarily related to work package two to the scientific community at three scientific conferences, including: 247th ECS Meeting (The Electrochemical Society) hosted in May 2025 in Montreal, Canada,[1] mESC-IS 2025: International Symposium on Materials for Energy Storage and Conversion, organised in September in Izmit, Turkey,[2] and the 248th ECS (Electrochemical Society) Meeting, October 2025, in Chicago (Illinois, US).[3]

Looking ahead, from 2026 onward, the focus will be on integrating the process into functional devices, ensuring successful implementation in the project's three demonstrators: self-charging textiles, self-powered structurally integrated sensors and graphene/Si anodes for Li-ion batteries for space applications.

Design and assembly of Li-ion battery (LIB) cells

Work package three focuses on the design and assembly of Li-ion battery (LIB) cells, with an emphasis on the preparation of laser-scribed graphene-based anodes and is led by Pleione Energy GmbH (PLE).

This group designs LIB cells incorporating anodes fabricated using the laser-assisted method developed by FORTH in work package two, investigates the ageing mechanisms of graphene-based LIB cells and establishes performance benchmarks.



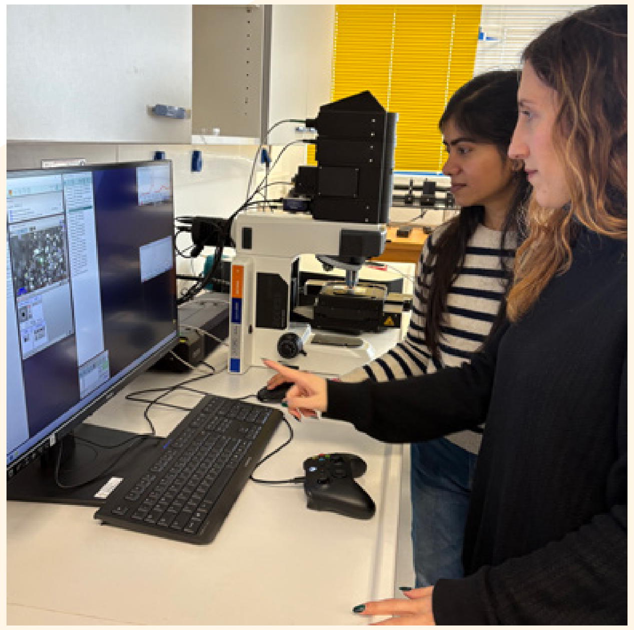
Deposition of GO precursor on textiles using the spraying method. Credit: GRAPHERGIA

In 2025, PLE developed a robust pouch cell assembly protocol starting from commercial graphene/graphite anodes, yielding essential insights into material handling and manufacturing steps, and expect to optimise and integrate laser-scribed electrodes at FORTH (in relation to work package two).

In parallel, the University of Rome, Sapienza (URM) has been developing a coherent Raman spectroscopy system tailored for the study of highly fluorescent, complex electrolyte liquids used in LIBs. The system integrates nonlinear Raman techniques, i.e. Stimulated Raman Scattering (SRS) and Impulsive Vibrational Spectroscopy (IVS), offering high sensitivity, fast acquisition and inherent fluorescence suppression. To benchmark this system, URM performed an *operando* vibrational study of solvation and electrochemical processes in Zn-based deep-eutectic solvent electrolytes.

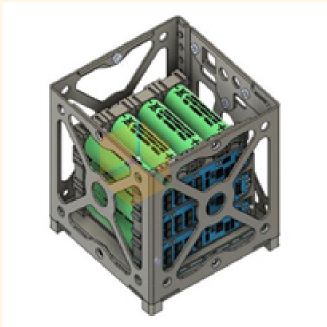
Towards 2026, the successful completion of these steps will certify the cells for assembly into our CubeSat demonstrator, ensuring they satisfy the stringent reliability, safety and performance requirements of space applications.

GRAPHENE FLAGSHIP ANNUAL REPORT 2025



Electrode characterisation via Raman Spectroscopy.
Credit: GRAPHERGIA

Graphene-based Lithium-ion cylindrical battery cells and battery module assembly integrating multiple lithium-ion cells for space applications.
Credit: Pleione Energy GmbH



Advanced electrical modelling and efficient power management
Work package four focuses on advanced electrical modelling and efficient power management of triboelectric nano-generators (TENGs) for energy harvesting and self-powered sensing IoT applications and is led by the Université Gustave Eiffel/ESYCOM lab (UGE).

In 2025, the team successfully applied the new TENG system optimisation criterion to a class of conditioning circuits particularly suited to transducers with low capacitance variation used in the case of textile-based TENGs, effectively coupled with electrochemical energy storage devices, such as micro-flexible supercapacitors.

The power management TENG solution will run on system-on-chip (SoC) that would enable wireless communication, support low-power operation and provide sufficient processing capabilities. This year, the partners conducted a power-consumption overview of low-power wireless SoCs. Power consumption is a critical component of an energy-harvesting system, and an optimal choice should be made based on the available harvested energy and the energy required for signal processing and communication.

Additionally, a schematic of a TENG-based modular IoT system was developed. The designed system covers the main aspects of an IoT system, including signal sensing, processing and wireless communication, while integrating energy harvesting.

These developments were presented to the scientific community at the ISE20 conference, held in September 2025 in Matsue, Japan.[4]

Design, manufacturing and testing
Work package five focuses on the design, manufacturing and testing of representative technology demonstrators and is led by ADAMANT Composites Ltd. (ADA).

During 2025, the group developed the framework for three GRAPHERGIA demonstration cases. The tasks for their development are scheduled to begin in March 2026.
These include:

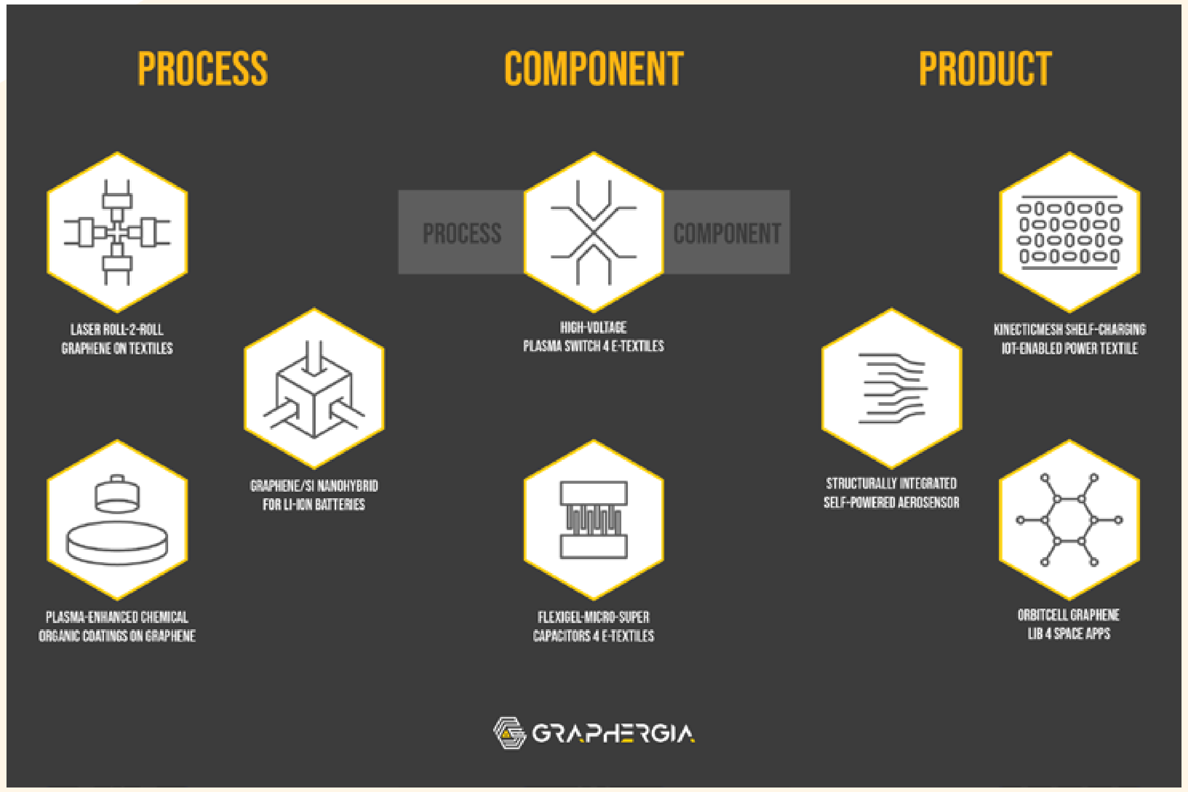
- **Demo 1** "All-in-one self-charging textile capable of energy harvesting and storage" will develop and validate an all-in-one, wearable or upholstery-integrated self-powered textile system that combines energy harvesting and storage.
- **Demo 2** "Self-powered structurally integrated sensor for aerospace structures" designs, fabricates and structurally integrates a miniaturised TENG-powered wireless strain/temperature sensor into aerospace composite materials.
- **Demo 3** "CubeSat - Advanced graphene-based LIB module prototype for space applications" constructs and functionally validates a graphene-based lithium-ion battery module for space applications.

Moreover, the demo preparation efforts focused on developing an eco-design framework tailored to the project's textile-based and battery products and processes. Additionally, alignment with the EU regulatory landscape was verified through an extensive review of current and emerging eco-design standards, regulations, and circular-economy policies at the European level.

Life cycle assessment, sustainability and eco-design
Work package six is dedicated to life cycle assessment, sustainability and eco-design approach, and is coordinated by Next Technology Tecnotessile (NTT).

This group assesses environmental burdens by identifying and quantifying energy and raw material inputs through a life cycle assessment (LCA). NTT and the involved teams have defined the LCA goals and scope, in compliance with two key standards: ISO 14040 and ISO 14044. In addition, to determine the life cycle cost (LCC) and cost feasibility of the different stages associated with the development of the target products. The analysis will be conducted in parallel with the LCA. The last building block of sustainability is the definition of an eco-design strategy to minimise future waste in the technological development process. In 2025, the NTT initiated data collection for LCA, LCC and eco-design within the consortium and developed and distributed data-collection templates to technical partners.

To disseminate our approach, GRAPHERGIA hosted a webinar in March dedicated to sustainability and eco-design, and NTT joined two sister projects' workshops as a featured speaker.



GRAPHERGIA's eight key exploitable results.
Credit: GRAPHERGIA

DISSEMINATION, EXPLOITATION AND COMMUNICATION
Work package seven focuses on the dissemination, exploitation and communication of project results. The leading partner is AUSTRALO Marketing Lab (AUS).

GRAPHERGIA aims to share key results and research activities through open access while preserving related intellectual property rights. To this end, the project implements an overall impact strategy comprising communication, dissemination and exploitation for target stakeholders, including graphene producers, smart textile and battery manufacturers, and the related scientific community.

In 2025, GRAPHERGIA continued promoting active stakeholder participation through targeted channels, thereby increasing visibility and establishing a robust stakeholder network around the project. This approach fosters GRAPHERGIA's impact beyond the project lifetime and facilitates the potential market uptake of its key exploitable results.

GRAPHERGIA partners have demonstrated a strong commitment to the project through active communication via social media and the website, and through robust dissemination in several resulting scientific publications and at key international scientific events. Moreover, this collaboration in the creation of the GRAPHERGIA hub, a platform for involved stakeholders with a keen interest in the project's three key research areas: graphene, smart textiles and Li-ion batteries, along with their novel applications.

In the second year, GRAPHERGIA effectively communicated its main activities and results through targeted channels, including social media platforms, where it has garnered over 2,100+ followers (LinkedIn, X & BlueSky), a bi-annual newsletter[5] with over 600 subscribers, and the project website (graphergia.eu), which features 70 blog articles highlighting project updates and news. Moreover, GRAPHERGIA has produced six videos featuring its researchers, all available on YouTube.

In 2025, GRAPHERGIA achieved strong dissemination, including five peer-reviewed journal publications and five conference presentations. All publications are open access.[6] Additionally, within the GRAPHERGIA hub, a series of scientific webinars was held to discuss various aspects of related research topics, such as laser-assisted graphene deposition and eco-design for graphene-based products. To foster exchange with manufacturers and industry stakeholders, the partners presented GRAPHERGIA at two international exhibitions: LOPEC (Large-area, Organic & Printed Electronics Convention) in February 2025 and DEFEA (Defence Exhibition Athens) in May 2025.

Moreover, the exploitation task is laying the groundwork for innovation management beyond the project's duration. The project is expected to deliver eight key exploitable results (KERs) spanning components, products and processes.
This year, the partners have developed their initial individual plans for exploitation and intellectual property rights management, thereby facilitating further commercial, technical or scientific exploitation of these results. To support this, partners compiled a market insights report with a focus on the three target markets for the project's demo cases: e-textiles, lithium-ion batteries for spatial applications and smart sensors for aerospace structures.

Graphene Week 2025 SAFARI and GRAPHERGIA workshop line-up.
Credit: GRAPHERGIA

POWERED BY THE GRAPHENE FLAGSHIP

In the past year, GRAPHERGIA has conducted 12 collaborative activities with Graphene Flagship sister projects, thereby reaching an even wider community of stakeholders and graphene enthusiasts in Europe and beyond. This collaboration is not limited to joint communication and dissemination; from a technical perspective, the project has initiated the exchange of materials and device components, with the ARMS, 2D-PRINTABLE and SAFARI projects.

Another remarkable example of Graphene Flagship's support for GRAPHERGIA is the co-production of a podcast series titled "The Human Side of Graphene", which aims to disseminate the impact and benefits of the Graphene Flagship project's research on graphene and 2D materials for society. The first two episodes were recorded during Graphene Week 2025. The Graphene Flagship team assisted with the invitation of speakers (from the Graphene Flagship, MUNASET, 2D-BioPAD and ARMS projects) and managed the on-site recording and post-production of the episodes. The fruit of this collaborative work is released in January 2026 with the first episode dedicated to Graphene Biosensors in Healthcare.[7]

Furthermore, GRAPHERGIA was involved in five workshops organised by Graphene Flagship members. In May 2025, three workshops took place: one session, dedicated to "Safe and sustainable by design: graphene and MXenes", was hosted by the SAFARI project in Athens, Greece, the second was a Graphene Flagship Digital Workshop: "Advancing Sustainability in 2D Materials" and the third one was "the EU-Korea Workshop", which was organised in Strasbourg, France.[8] Graphene Week 2025, organised in September 2025 in Vicenza (Italy), offered a stage for two more workshops; the first one, on "Life Cycle Assessment", was hosted by the GIANCE project and included a speaker from GRAPHERGIA. The second one, titled "Safe and Sustainable-by-Design 2D Materials: Manufacturing Processes and Applications in Energy, Electronics, and Biotechnology", was co-hosted by GRAPHERGIA and SAFARI.[9]

ON THE HORIZON

Over the next year, the project will move from lab-scale proofs to pilot-scale practice. The focus is on translating the laser-assisted methods to continuous processing, strengthening inline quality control, and transforming the technology into compelling demonstrators that combine conductive textiles, gel-electrolyte micro-supercapacitors, binder-free anodes and energy-harvesting layers with power-management electronics. Durability in real use (e.g. bending, flexing, abrasion) and user safety will be among our targets.

GRAPHERGIA will also broaden engagement with market-oriented stakeholders through its Industrial Reference Group, co-shaping acceptance criteria and a credible path towards pre-certification. In parallel, we will update our sustainability work, including life cycle and eco-design thinking, so that responsible material choices and end-of-life options match performance gains.

Key challenges, such as balancing conductivity with porosity and adhesion, ensuring repeatability at scale, and addressing environmental health/safety considerations, will be addressed through tighter process-window mapping, inline metrology and materials optimisation. On the exploitation side, GRAPHERGIA plans to mature the pre-defined set of key exploitable results and explore first-deployment pilots with early adopters, laying the groundwork for impact beyond the project's lifetime.

SURPRISE ME

An outcome that genuinely surprised us is that a carefully tuned laser pass can write highly conductive, strongly adherent graphene films directly on very heat-sensitive substrates, such as synthetic textiles, paper and thin polymer foils, without flame retardants or wet chemistry. The beam briefly heats only a microscopic surface layer, reducing GO *in situ* while leaving the bulk material intact, yielding clean, patterned conductivity where other reduction approaches usually fail. Furthermore, by switching precursors and substrates, the same idea was produced, in one step, graphene/Si hybrid anodes directly on copper current collectors, without binders or pre- or post-treatments. This single-tool, "dry approach" points to a practical route from lab recipes to manufacturable components for flexible electronics and next-generation energy storage.

Energy

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Spyros Yannopoulos, University of Patras and Foundation for Research and Technology – Hellas, Greece

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Deutsches Zentrum für Luft - und Raumfahrt e.V., Germany
Next Technology Tecnotessile, Italy
Pleione Energy GMBH, Germany
Adamant Composites Ltd., Greece
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EMPHASIS
SOLiD

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Ocsial Europe SARL
Armor Battery Films SA
Coatema Coating Machinery GmbH
Tomas Bata University in Zlin
Bern University of Applied Sciences

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MUNASET

Multiparametric nanoelectronic biosensors for therapy response testing

OUR GOAL IS TO CREATE a next-generation biosensor platform that integrates multiple existing technologies into a unique device capable of transforming the way biochemical reactions and physiological interactions are studied. By leveraging 2D graphene, we aim to demonstrate several advantages over conventional tools:

- **Enhanced biosensing performance:** Low detection limits, minimal signal drift, high chemical stability and biocompatibility enable sensitive and selective real-time detection of biomarkers.
- **Versatile surface chemistry:** π–π stacking of linker molecules on graphene allows the attachment of capture peptides for multiple analytes and supports different detection principles on the same device.
- **Novel sensing mechanism:** Specific charge removal by proteases ensures clear, reproducible signals with high reliability.
- **Integrated CMOS readout:** Supports robust multi-analyte detection in a compact and scalable format, enabling efficient, real-time measurements.

Together, these features position the MUNASET platform as a powerful tool for both fundamental research and clinical applications, paving the way for more precise and personalised therapeutic strategies.

> The MUNASET project aims to develop graphene-based devices to help doctors monitor patients with depression and other psychiatric disorders undergoing therapy. The envisaged test is fast and easy to use, requires only blood samples, and can be performed at the point of care to support personalised therapies. It has the potential to greatly improve treatment outcomes for psychiatric diseases."

Alexey Tarasov
Project Coordinator
Kaiserslautern University of Applied Sciences

PROGRESS IN 2025

The most significant achievement in 2025 has been the experimental demonstration of the sensing principle underlying the detection of protease biomarkers. These results have been published in Biosensors and Bioelectronics.[1] We have developed a highly sensitive plasmonic, peptide-based biosensor for detecting a protease biomarker (MMP-9). The sensor outperforms state-of-the-art methods, providing faster detection, enhanced sensitivity and additional information on binding kinetics, surface coverage and molecular layer thickness.

Quantitative detection of MMP-9 is typically performed using bioanalytical detection kits such as enzyme-linked immunosorbent assay (ELISA), which are time-consuming and do not allow real-time, label-free monitoring. To overcome these limitations, we employed multi-parametric surface plasmon resonance spectroscopy (MP-SPR) with immobilised short synthetic peptides as MMP-9 substrates. This represents the first MP-SPR biosensor based on short peptides for monitoring MMP-9 activity, enabling rapid detection within minutes and providing real-time information on binding kinetics, surface coverage and peptide layer thickness.

Graphene has emerged as a highly promising material for enhancing plasmonic sensor performance. Our work, featured on the front cover of *Advanced Healthcare Materials*, demonstrated that integrating a single graphene layer with SPR interfaces can increase sensor signals by up to ~600%, greatly improving sensitivity for biomolecular interactions. This establishes graphene-enhanced SPR as a powerful platform for next-generation optical biosensors.[2]

In parallel, graphene-based field-effect transistors (GFETs) offer a compact, scalable, and cost-effective alternative to conventional plasmonic sensors. We have published a direct comparison of GFET and SPR biosensors in *Advanced Science*, demonstrating that GFETs can achieve performance comparable to SPR while enabling smaller, cheaper and more easily integrable devices suitable for point-of-care applications.[3]

Building on these advances, our broader research efforts address biomarkers relevant to major depressive disorder (MDD) and other complex diseases. To contextualise these developments and outline future directions, we have published a Perspective article in 2D Materials, discussing recent progress, challenges and opportunities in graphene-based biosensors for mental health diagnostics.[4]

DISSEMINATION AND EXPLOITATION

In 2025, we updated the MUNASET website with a refreshed, dynamic look and feel, and added new sections, including "Meet the Team" and "Publications", to enhance visibility and accessibility of our work.

We actively engaged with the scientific community through participation in the Biosensors Workshop of the 2D-PL Project and the GIANCE & MUNASET Workshop on "Advances in Graphene Materials and Applications", as well as several sessions at Graphene Week 2025. Within the Roadmap Working Group, we contributed to the development of the upcoming Graphene Flagship Roadmap and the 2D Material-based Sensing Technology Innovation Roadmap for Biomedical Applications, strengthening the alignment of MUNASET activities with broader European graphene initiatives.

MUNASET contributed to the Graphene Flagship's first podcast shot at Graphene Week 2025.
Credit: Giò Tarantini/ Gruppo Tonello

Regarding exploitation, we have advanced our work in Technology Watch and Value Chain Gap Analysis, generating valuable insights to guide the development, scaling and commercialisation of our biomedical sensor technologies. These activities are directly informing our exploitation strategy and supporting the translation of the MUNASET platform into clinically relevant diagnostic tools.

POWERED BY THE GRAPHENE FLAGSHIP

Participation in the Graphene Flagship has been a key enabler of the MUNASET project. The initiative's ecosystem has provided access to cutting-edge graphene research, specialised expertise and a highly collaborative network focused on translating graphene technologies into real-world applications. This environment has allowed us to leverage state-of-the-art materials, exchange knowledge with leading scientists and accelerate the development of our graphene-based biosensor platform.

The Graphene Flagship's shared infrastructure, technical resources and interdisciplinary collaboration have been instrumental in overcoming key technical challenges and fostering innovation. As a result, the project has advanced more rapidly toward its goal of developing a fast, sensitive and reliable diagnostic tool, supporting personalised therapeutic strategies for major depressive disorder.

Cover art for the Advanced Healthcare Materials issue containing the MUNASET publication.

ON THE HORIZON

Looking ahead, the MUNASET project is well positioned for the next phases of development. The results achieved so far, together with effective coordination mechanisms and strong inter-partner collaboration, provide a solid foundation for continued success. The consortium remains focused, highly motivated and fully committed to delivering high-quality results while maximising the project's impact throughout the remainder of its duration.

Future efforts will concentrate on extending the sensing platforms toward robust multianalyte detection and on systematically addressing interference effects that arise in complex biological environments. Particular emphasis will be placed on evaluating sensor performance in increasingly realistic sample matrices, improving selectivity and reliability and ensuring reproducible operation across devices and measurement campaigns. These activities will support the development of scalable, versatile biosensor arrays capable of operating under clinically relevant conditions.

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GRAPHENE FLAGSHIP ANNUAL REPORT 2025

SURPRISE ME

In 2025, we completed our first end-to-end value chain analysis spanning materials, biointerfaces and device architectures. This integrated assessment yielded several unexpected and high-impact insights that significantly strengthen the technological and commercial positioning of the MUNASET platform:

- **Graphene as a highly sensitive material:** We demonstrated that high-quality, reproducible graphene sensors – both as standalone devices and when CMOS-integrated – can be fabricated with performance characteristics and scalability that can translate into clear and attractive market value.
- **Robust biofunctionalisation without performance loss:** Contrary to common assumptions, stable and reproducible peptide attachment to graphene can be achieved without compromising its intrinsic sensitivity. This finding can enable higher biosensor reliability and sensitivity, particularly in complex, real-world biological samples.
- **Quantitative and clinically relevant detection:** The platform delivers reliable, quantitative protease detection with well-defined sensitivity and selectivity, meeting clinically relevant performance requirements rather than proof-of-concept benchmarks.
- **Optimised peptide probes as key value drivers:** Highly optimised peptide probes were identified as critical enablers of selective protease recognition, providing both high specificity and sensitivity and significantly strengthening the diagnostic potential of the technology.

Together, these findings reveal that the value of the MUNASET platform does not lie in a single breakthrough component, but in the coherent integration of materials, interfaces and devices – transforming advanced biosensing concepts into a viable diagnostic technology.

Biomedical

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GRAPH-OCD

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University of Nantes, INSERM U1229 Regenerative Medicine and Skeleton
Paragraf Ltd
University of Helsinki, Institute of Biotechnology (HILIFE)

MUNASET
PART OF THE GRAPHENE FLAGSHIP

GRAPHENE FLAGSHIP ANNUAL REPORT 2025

2D-BIOPAD

Supple Graphene Bio-Platform for point-of-care early detection and monitoring of Alzheimer's Disease

THE 2D-BIOPAD PROJECT will create an easy-to-use decision support tool to help detect Alzheimer's disease at an early stage. It will use advanced graphene materials to run a fast, minimally invasive test that can measure up to five important Alzheimer's biomarkers in real time. The tool will be tested in clinical studies in Finland, Greece and Germany to prove that it is safe and effective.

> Last year 2D-BioPAD made great strides in discovering new aptamers for the recognition of Alzheimer biomarkers, networking with key stakeholders and in developing point-of-care devices for achieving their detection in blood samples."

Aristeidis Bakandritsos
Project Coordinator
Czech Advanced Technology and Research Institute (CATRIN) at Palacký University

PROGRESS IN 2025

Requirements & System Architecture

By September 2025, ICN2 (Catalan Institute of Science and Nanotechnology) together with all technology partners, provided a refined version of the 2D-BioPAD system architecture, which is designed to support minimally invasive and cost-effective point-of-care detection of Alzheimer's disease biomarkers using advanced two dimensional (2D) material-based biosensing. The system combines complementary sensing approaches: electrochemical and graphene field-effect transistor (GFET)-based sensors with either aptamers (aptasensors) or antibodies (immunosensors), towards identifying the most reliable approach per biomarker. Key integration technical challenges and their solutions were identified, allowing flexibility for future improvements throughout the project.

Biomarkers binding and quantitative analysis

Significant progress was made on identifying aptamers targeting Aβ1-40, Aβ1-42, p-Tau217, GFAP and NfL, alongside validating the Aristotle University of Thessaloniki's (AUTH) protocol for conjugating aptamers to magnetic nanoparticles (MNPs) and testing their interaction with target biomarkers. NOVAPTECH achieved multiple high-affinity aptamers for GFAP and NfL, including truncated variants, completed selectivity studies for NfL and continued new selections for p-Tau217, while exploring sandwich assay formats to improve binding performance. AUTH synthesised and distributed bare MNPs and MNP-aptamer conjugates at different concentrations to partners for downstream integration and testing.

In parallel, CeADAR evaluated AI-based models and initiated further AI routes to support aptamer selection and optimisation, with particular emphasis on overcoming challenges for p-Tau217 and Aβ targets. Overall, 2025 consolidated experimental and computational efforts, aligning partners on clear next steps toward robust, quantitative biomarker binding assays.

Graphene biosensing and AI-assisted characterisation

During 2025, the partners made steady progress on graphene-based sensing technologies. UP-CATRIN led the work by testing seven synthesised graphene derivatives and identified the best-performing derivative is a doubly functionalised graphene, where the second functionality is a biorepellent molecule also promoting water solubility. This derivative offers higher reproducibility than the single-functionalised graphene derivative and an improvement of 125% to the generated electrochemical signal. UP-CATRIN also carried out control experiments in square wave voltammetry (SWV) and confirmed that no signal appears when the target is absent. They shared XPS data with CeADAR, about elemental analysis and bond configuration of graphene derivatives.

CeADAR advanced the AI-assisted deconvolution work by proposing new methods to automate data analysis. UP-CATRIN's work is ongoing, focusing on evaluating graphene derivatives functionalised with aptamers for GFAP and NfL.

Meanwhile, ICN2 made significant progress with their reduced graphene oxide (rGO) electrodes[2] for the electrochemical sensors. The capacitive response of the rGO-AuNP-based laser-nanostructured platform was studied by impedance-derived electrochemical capacitance spectroscopy (ECS).[1] For Aβ1-40 detection, results achieved showcase a dissociation constant in the low picomolar range (K_D = 23.25 pM (≈100 pg/mL)), a limit of detection (LoD) of 18.0 pM (≈78 pg/mL), and a limit of quantification of 26.5 pM (≈115 pg/mL). These results place the sensor's optimal working range directly within clinically reported plasma Aβ1-40 concentrations. Similarly, for Aβ1-42, a clear discrimination between negative and positive samples and an LoD of 41.5 pM have been achieved.

Excellent progress was also made on the GFET-based sensors. GRAPHEAL successfully integrated NOVAPTECH's aptamers targeting GFAP and NfL, while also exploring commercial antibodies for Aβ1-40, Aβ1-42, p-Tau217, GFAP and NfL, managing to immobilise both probe types on the same CVD graphene surface, delivering a hybrid aptasensors/immunosensor. Targeting initially GFAP and NfL, GRAPHEAL demonstrated a first working prototype of a GFET aptasensor with picomolar (~4 pM) sensitivity, capable of detecting 70 pM in human plasma.

2D-BioPAD point-of-care decision support tool/device

GRAPHEAL led the work on device ergonomics and overall design, including any additional hardware and software needs. A first prototype demo of the GFET-based device was shown at Graphene Week 2025. The project also used paper microfluidics to capture red blood cells and continued working on making the cartridge smaller. By the end of the year, ICN2 and GRAPHEAL agreed on next steps to advance the electrochemical sensor, integrate the app and electronics and collaborate on microfluidics approaches to support further development and miniaturisation.

Figure 1. 2D-BioPAD GFET-based prototype biosensing platform. Credit: 2D-BioPAD

Figure 2. Webinar on the basics of European Regulations for medical devices and *in-vitro* diagnostics, organised by EVNIA on 10 February 2025.

Clinical Pilot Studies Design, Deployment, Evaluation & Validation

Throughout 2025, University of Eastern Finland, together with EVNIA, ICN2, GRAPHEAL, the Greek Association of Alzheimer's Disease and Related Disorders and the Central Institute of Mental Health in Manheim, worked on refining the clinical pilot studies protocols, considering the progress made on the device and the requirements of the *in vitro* diagnostic medical devices' regulation (IVDR). The University of Eastern Finland led the preparation of the retrospective study, including ethical approval, sample-sharing agreements, and templates for sample shipment. They also coordinated discussions on plasma benchmarking and shipping and worked with partners to keep system requirements clear and simple.

EVNIA significantly supported all steps to address IVDR requirements, organising an online public webinar for the Graphene Flagship community and joint consortium workshops focused on the specifications of the 2D-BioPAD decision support tool and its hazard analysis, where all partners worked together to better position the 2D-BioPAD device to regulatory requirements. The University of Eastern Finland and EVNIA also worked together to align on finalising study documentation, including the Case Report Forms (CRF).

This collaboration launched the activities of the retrospective clinical pilot study, having its protocol approved by Ethical Committees, material transfer agreements (MTA) signed and 60 well-characterised plasma samples awaiting to be shipped to the technical partners to technically validate the biosensors.

DISSEMINATION AND EXPLOITATION

During 2025, the project continued to share its work and results with a wide range of people, including researchers, healthcare professionals, industry, policymakers and the general public. Communication activities followed the agreed plan and were updated as the project progressed.

Project partners actively engaged in major international events, including Graphene Week 2025 and NanoBalkan 2025, and co-organised a series of dedicated workshops addressing key topics such as brain health, biomedical applications of graphene and regulatory requirements for medical devices.

Events played a central role in 2025. Over the course of the project, partners participated in more than 50 external events, spanning conferences, symposia and stakeholder meetings. In addition, seven project-led workshops and events were successfully organised, surpassing the original targets set at the outset of the project.

From a scientific perspective, 2025 was a particularly productive year. The project achieved strong publication output, with peer-reviewed journal articles (x3) and conference papers published, bringing the cumulative total to six journal publications and 17 conference contributions.

Digital outreach efforts also continued to grow. Engagement through the project website and social media channels increased steadily, while project videos exceeded 4,400 views. Collectively, these dissemination and communication activities enabled 2D-BioPAD to reach more than 28,000 stakeholders across the research, industry, healthcare and policy communities.

Finally, in terms of exploitation, Q-PLAN has supported the consortium to refine the 2D-BioPAD Key Exploitable Results (KERs), while organising co-creation activities to identify several 2D-BioPAD business models, considering four customer segments. With a first version of a business plan drafted, the consortium has fully acknowledged the market potential of its KERs, which fuelled the engagement with key market actors, including pitching to venture capitalists and strategic partnerships with industrial tech companies. This engagement provided valuable feedback, including market validation, boosting our R&I activities.

GRAPHENE FLAGSHIP ANNUAL REPORT 2025

Figure 3. 2D-BioPAD and MUNASET partners at GW2025 after the jointly organised Biomed Parallel Session. Credit: 2D-BioPAD

POWERED BY THE GRAPHENE FLAGSHIP

Being part of the Graphene Flagship has strongly supported the goals of 2D-BioPAD. As one of the two core projects focused on biomedical applications, 2D-BioPAD has benefited from close alignment with the Graphene Flagship's strategy through active participation in several working groups and shared reporting activities. This has helped ensure that biomedical needs are well represented within the wider 2D materials community.

In addition, 2D-BioPAD has built links with seven Graphene Flagship initiatives and has carried out joint activities with several of them. In particular, collaboration with the MUNASET project included shared workshops, joint dissemination and regular scientific exchange. Additional interactions with GRAPHERGIA, SAFARI, GIANCE, Next2Digits and 2D-PRINTABLE have supported knowledge sharing across materials development, processing, and application areas relevant to healthcare. For instance, 2D-BioPAD, together with MUNASET, have engaged with GRAPHERGIA and SAFARI to draft a joint Technology Innovation Roadmap on 2D Materials-based sensing technologies for biomedical applications, under the guidance of the Graphene Flagship.

Participation in Graphene Flagship events and communication activities, such as Graphene Week, STF workshops and contributions to Graphene Flagship annual reports, has increased the visibility of 2D-BioPAD's work and results. Overall, involvement in the Graphene Flagship has provided 2D-BioPAD with a strong network, clear coordination and valuable collaboration opportunities that directly support the project's objectives.

ON THE HORIZON

2026 will be pivotal for 2D-BioPAD. The consortium will focus on further optimising the sensor architecture and assay conditions to push detection limits toward the femtomolar range, which is critical for operation in complex biological matrices such as plasma.

Starting from the probes, the consortium now has access to high-affinity aptamers and FDA-approved antibodies for the target biomarkers. Following the proven conjugation protocol, several batches of MNP-aptamer conjugates will be available, to support the integration process and improve the results of the biosensing platforms.

On the clinical pilot studies side, work will focus on using real clinical samples in the context of the retrospective clinical pilot study, to technically validate the analytical performance of the 2D-BioPAD biosensors. In parallel, we will submit the refined prospective clinical pilot study protocol for ethical and regulatory approval, aiming to initiate the prospective study within 2026, bringing the device in the hands of healthcare professionals to test it in front of patients.

In addition, the project will strengthen its scientific visibility and outreach. Planned activities include participation in Graphene Week 2026 in Porto, contribution to a joint workshop with MUNASET featuring a dedicated biomedical session, as well as our participation at the Alzheimer's Disease International (ADI) conference in Lyon. Efforts will also be directed toward joint scientific publications in collaboration with other synergy projects.

Continued improvements to the prototype and clinical outcomes will provide valuable information for evaluating and validating our technologies while, paving the way for broader dissemination and future exploitation. Overall, 2D-BioPAD will continue to move forward with many ongoing activities. Stay tuned!

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SURPRISE ME

One of the most surprising outcomes in 2025 has been how our research moved from an initial idea to a mature, reliable high Technology Readiness Level (TRL) solution.

First, 2D-BioPAD delivered high affinity aptamers for GFAP and NfL, with full and truncated versions that offer short and specific probes for these analytes. Second, stable core-shell Fe304/Au magnetic nanoparticles have been successfully synthesised and extensively tested to support more effective readings on the sensors. The team has also validated a method to link them together (conjugation protocol) making both results available (separately or together) to the research community for pushing the limits of biosensing for Alzheimer's disease and beyond.

Together with our significant progress on biosensing technologies, these advances have allowed 2D-BioPAD to clearly demonstrate the strength and reliability of its scientific foundation. As a result, the project has opened new opportunities for industrial uptake, stakeholder engagement and downstream innovation.

Finally, the clearance from FDA of the first blood test used in diagnosing Alzheimer's Disease during 2025,[3] has validated the original goal of the project, further fuelling our commitment towards more accessible blood-based diagnostics for Alzheimer's Disease.

Biomedical

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International Iberian Nanotechnology Laboratory

2D BioPAD

GRAPHENE FLAGSHIP ANNUAL REPORT 2025

GIANCE

Transforming industries with sustainable graphene-enhanced materials

DURING 2025, the GIANCE project progressed from advanced laboratory development toward demonstrator-level validation under relevant operational conditions, strengthening the technological maturity of graphene-related materials (GRM) and accelerating their integration into automotive, aerospace, hydrogen and water-treatment systems.

The consortium focused on consolidating material formulations, upscaling manufacturing processes, integrating materials into functional prototypes and validating performance through physical and virtual testing, advancing circularity strategies and reinforcing industrial exploitation pathways.

A STRONG AND ALIGNED EUROPEAN CONSORTIUM

The consortium of 23 partners across ten countries continued to demonstrate effective collaboration across the full value chain, between OEMs, research centres and SMEs. Cross-work package integration ensured smooth transition from material optimisation (TRL5-6) to industrial demonstration (TRL6-7), strengthening the European graphene value chain.

Requirements consolidation and regulatory alignment
Technical specifications were refined based on prototype testing feedback and strengthened regulatory mapping (REACH, hydrogen regulations). Lifecycle-driven design criteria were further embedded into material selection and process decisions to ensure recyclability and sustainability targets alignment.

Advanced material optimisation and pilot-scale upscaling
Pilot-scale production of optimised graphene nanoplatelets and few-layer graphene improved dispersion techniques and batch reproducibility were achieved. Variability in composite formulations was reduced, enabling more reliable integration into structural and functional components. Enhanced composites demonstrated improved strength, corrosion resistance and hydrogen barrier performance.

Sustainable manufacturing and circular processing
Laser-based surface functionalisation was validated at pilot-line scale while reducing dependency on chemical-intensive treatments. Recycling trials and design-for-disassembly strategies advanced circular manufacturing approaches and reduced CO_2 footprint.

Circularity considerations were integrated into component redesign. Initial mechanical recycling trials for selected composite systems were performed, and design-for-disassembly principles were incorporated into demonstrator development. These activities represent tangible progress toward achieving the recyclability ambitions defined in the project objectives.

> 2025 has marked the transition from material optimisation to integrated industrial validation. GIANCE is consolidating its pathway toward TRL6-7 demonstrators while strengthening circularity and exploitation readiness."

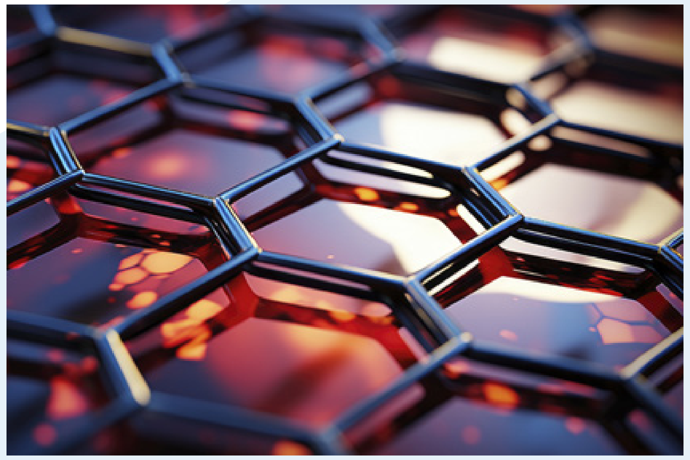
Rosa Maria Araujo Rivero
Project Coordinator
Eurecat Technology Centre

Industrial demonstration and pre-market validation
Full-scale corrosion-resistant components were tested in automotive environments. Aerospace panels with embedded sensors were validated under load conditions. Hydrogen storage systems underwent pressurised cycling validation, advancing selected applications close to TRL 7. Testing, validation and long-term reliability accelerated ageing, fatigue resistance, thermal cycling and hydrogen permeability tests confirmed improved durability and monitoring capabilities. Digital modelling tools supported predictive maintenance strategies.

Life-cycle assessment and techno-economic evaluation
Life-cycle assessments and life-cycle cost modelling were intensified. Preliminary results indicate reductions in material waste and energy consumption compared to conventional systems. Extended component durability contributes to improved sustainability and economic competitiveness.

DISSEMINATION, COMMUNICATION AND EXPLOITATION

In 2025, GIANCE significantly strengthened its dissemination and communication impact, consolidating its scientific visibility and industrial outreach across Europe and beyond. With over 40,000 LinkedIn impressions, participation in 12 international events, high-level engagements at Graphene Week 2025 and the launch of the "Graphene in Action" podcast series, the project expanded its stakeholder network and reinforced its positioning within the Graphene Flagship ecosystem. Structured KPI monitoring, new documentary and video production pipelines and targeted exploitation actions are accelerating GIANCE's pathway from technological validation to market readiness.



The GIANCE team met at Graphene Week in Vicenza, Italy.
Credit: Giò Tarantini/ Gruppo Tonello

POWERED BY THE GRAPHENE FLAGSHIP

Collaboration within the Graphene Flagship ecosystem intensified through clustering activities, shared testing facilities and joint technical workshops, accelerating validation and strengthening Europe's leadership in graphene technologies.

LOOKING AHEAD TO 2026

The final project phase will prioritise full operational validation, certification pathways, business case consolidation and exploitation agreement structuring.

GIANCE continues to position itself as a driver of sustainable industrial transformation.

Composites

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ASSOCIATED MEMBER
Sixonia Tech GmbH

GIANCE
Fused with Sustainability

Association Mechanism

THE GRAPHENE FLAGSHIP Association Mechanism opens the initiative to a broader ecosystem of organisations and projects beyond its core consortium, enabling them to participate as Associated Members or Partnering Projects. Through this flexible framework, companies, universities, research institutes and externally funded projects can contribute complementary expertise, ideas and resources while aligning their activities with the Graphene Flagship's research and innovation priorities in graphene and other two-dimensional materials. By fostering collaboration and strengthening links with national and regional initiatives, the mechanism promotes knowledge exchange across the European two-dimensional (2D) materials community and ensures the continuity of long-standing collaborations. Participants gain access to a dynamic network of academic and industrial partners, new opportunities for joint research and innovation and greater visibility for their results within Europe's leading ecosystem for advanced materials innovation. Below are this year's highlights from some of the Graphene Flagship's 14 Partnering Projects and 53 Associated Members.

PARTNERING PROJECT: SIO GRAFEN
FOCUS: COORDINATION AND SUPPORT

SIO Grafen is the national Strategic Innovation Programme supporting the industrial graphene and 2D material development in Sweden. They have funded approximately 220 projects with 250 organisations over 11 years.

Among many activities in 2025, SIO Grafen organised the ISO meetings in nanotechnology, including graphene and other 2D materials, in Stockholm in May. Standards are a requirement for serious industrial uptake. Engagement in the standardisation process is therefore crucial for development of graphene industrialisation.

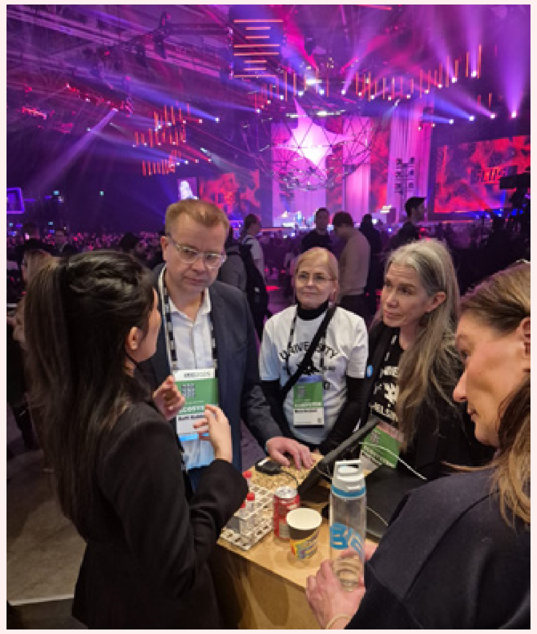
SIO Grafen have worked closely on standardisation, over the year, especially with the GrapheneEU and 2D Pilot Line projects.

SIO Grafen's ISO meeting in nanotechnology, including graphene and other 2D materials took place in Stockholm last May. Credit: Johan Ek Weis

PARTNERING PROJECT: BIOS3NSE
FOCUS: BIOMEDICAL

BioS3nse is a research-to-business project at the University of Helsinki (2025–2026) developing novel nanocoating technology – BioS3nse – to help manufacturers build next-generation biosensors. This technology uses graphene oxide (GO), which offers excellent electrochemical properties. BioS3nse incorporates proprietary custom-designed GO-binding peptides with a specific chemical surface treatment. In the past year, the project has continued to mature the technology to TRL 5, demonstrating its functionality in glucose and cortisol laboratory measurements. A Finnish patent application has recently been filed.

BioS3nse is currently in the customer discovery phase and looking for companies with whom to discuss future opportunities. The project is also seeking partners, both academic and commercial, to pilot and develop prototypes.



BioS3nse team explaining the applications of the technology at Slush 2025. Credit: University of Helsinki

PARTNERING PROJECT: 2DINTEGRATE
FOCUS: ELECTRONICS AND PHOTONICS

2DIntegratE partners performed a multiscale investigation of monolayer MoS_2 transistors, revealing for the first time contact-induced strain variations inside the channel. Their impact on the electron effective mass distribution and, consequently, on carrier mobility and contact resistance will be relevant for future ultra-scaled transistors applications. These results have been published in Small Science.[1]

2DIntegratE partners actively interacted with Graphene Flagship partners, by engaging in fruitful discussions and exchange of ideas during Graphene Week 2025 in Vicenza, Italy.

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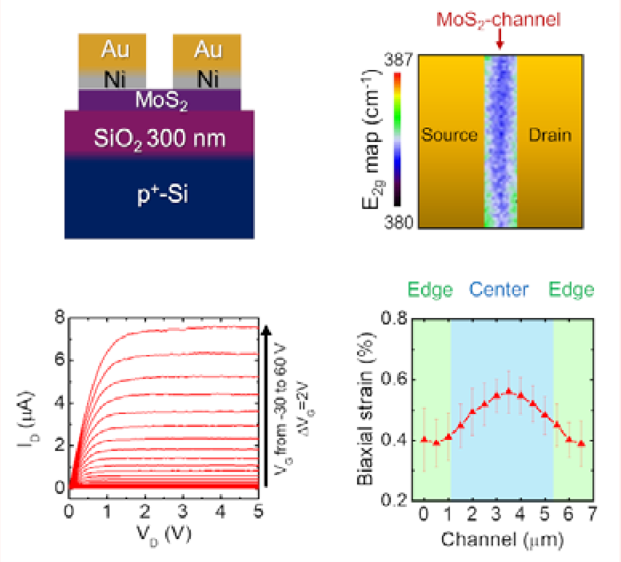

Schematic illustration, electrical characteristics and laterally resolved strain distribution inside the channel deduced from Raman mapping.

ASSOCIATE MEMBER: GRAPHENEST, S.A.
FOCUS: ELECTRONICS AND PHOTONICS

In 2025, Graphenest advanced its graphene-based EMI shielding materials by optimising dispersion quality, improving coating uniformity and validating 30+ dB shielding performance in industrial environments. We upgraded our production line with a solvent recovery system, enhanced inline quality control (ISO 9001 and ISO 14001) and increased throughput for applications in e-mobility and next-generation electronics.

Installation of Graphenest's solvent recovery system, enabling cleaner and more efficient production of graphene-based EMI shielding materials. Credit: Graphenest

ASSOCIATE MEMBER: UNIVERSITY OF MINHO
FOCUS: ELECTRONICS AND PHOTONICS

The activity of University of Minho group dealt with the theoretical examination of second-harmonic generation (SHG) in graphene. We investigated a graphene monolayer integrated within an attenuated total internal reflection configuration. Our analysis reveals that the excitation of surface plasmon-polaritons plays a central role in significantly boosting the efficiency of SHG in such a setup. We also demonstrate[1] that current response of a general single-band tight-binding system under pulsed excitation allows for the SHG even in the case of normal incidence.

References

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2. Alendouro Pinho, J. M. et al., Phys. Rev. B 2025, DOI: 10.1103/jxtp-18tx

PARTNERING PROJECT: MINERVA
FOCUS: 2D MATERIALS OF TOMORROW

The MINERVA project delivered major advances on amorphous boron nitride (aBN) as a novel disordered 2D material. Partners established scalable CVD growth of large-area aBN with controlled amorphicity and thickness. They characterised thermal, elastic and dielectric properties. Experiments were complemented with molecular dynamics and tight-binding simulations to establish structure-property relationships for ultrathin electronic and spintronic devices.

As a Graphene Flagship Partnering Project, MINERVA complemented the initiative's activities on 2D materials by introducing amorphous BN, a class of 2D material not previously explored within the Graphene Flagship. Interactions between partners enabled benchmarking of thermal, mechanical and dielectric performance.

References

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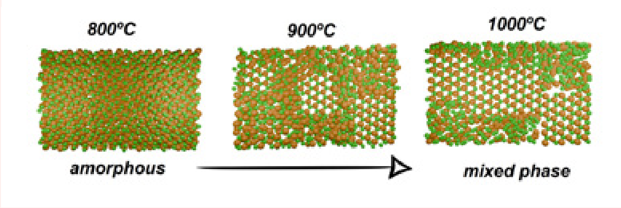


Schematics of the amorphous and mixed phase structure as a function of synthesis temperature. Credit: Daniel Capolat and Marianna Sledzinska (ICN2)

Top news of 2025

THE FUTURE OF HEATING IS GRAPHENE PAINT

Graphene Flagship partner BeDimensional has developed an innovative graphene-based heating paint that turns coated surfaces into efficient radiant heaters. When connected to simple electrodes, the conductive coating generates heat through the Joule effect, delivering uniform infrared radiation without mechanical components or visible radiators. Tests conducted with researchers from the University of Genoa show the technology can reduce energy consumption by around 40% compared with conventional electric radiators, while remaining easy to install on common building materials and suitable for both new construction and retrofits.

In 2025, the company demonstrated the first industrial implementation of the technology at its facility in Genoa, marking the transition from laboratory validation to real-world deployment. Developed with partners Estalia Coatings and Società Italiana Lastre, the graphene heating coating can be integrated into fibre-cement panels for buildings, offering a scalable, energy-efficient solution for the construction sector. The milestone highlights how graphene and other 2D materials are moving from research to market, supporting Europe's ambitions for sustainable buildings and advanced materials manufacturing.

SPEARHEAD SPIN-OFF AERO MATERIALS LAUNCHES ULTRA-LIGHT NANOMATERIAL

A spin-off from the Graphene Flagship AEROGrAFT spearhead project has launched a new company, AERO MATERIALS, to commercialise an ultra-light nanomaterial developed at Kiel University. The material – composed of more than 99.9% air – forms an open, conductive network of graphene-based nanostructures that is both extremely lightweight and highly functional. After more than a decade of research, the technology is now moving from the laboratory to market, demonstrating how Graphene Flagship innovations are translating into new European deep-tech ventures.

The aeromaterial enables electrically controlled heating and rapid mechanical actuation, allowing tiny structures weighing just milligrams to generate significant force. This capability opens opportunities in applications ranging from energy-efficient actuators and micropneumatics to self-cleaning filtration, optics and electromagnetic shielding for lightweight electronics such as drones. By replacing heavier mechanical systems with functional nanostructures, the technology could significantly reduce weight and energy consumption across a range of advanced industrial systems.

RESPONSIBLE USE OF GENERATIVE AI IN THE GRAPHENE FLAGSHIP

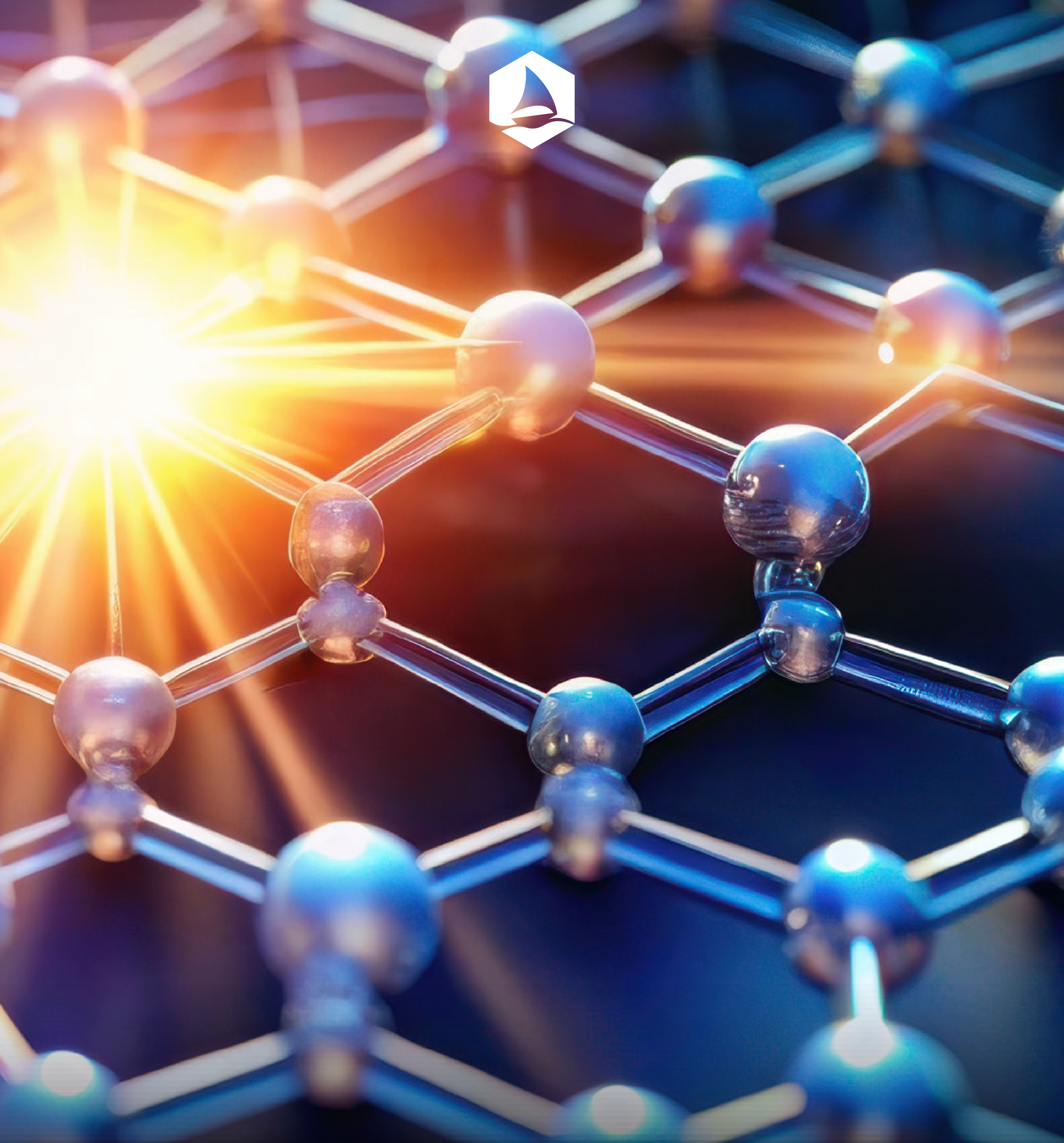
The Graphene Flagship has introduced a set of recommendations for the responsible use of generative AI (GenAI) across its research and project management activities. Developed during a workshop of the Project Managers Network in Vicenza ahead of Graphene Week 2025, the guidelines aim to support the safe and transparent integration of GenAI tools in Horizon Europe projects while maintaining high standards of research integrity and accountability.

Aligned with the European Commission's guidance and Horizon Europe principles, the recommendations outline best practices for using AI in scientific work, communication and administrative processes. By promoting responsible adoption of emerging digital tools, the initiative seeks to harness the benefits of GenAI while safeguarding data quality, ethical standards and trust in research outputs across the Graphene Flagship community.

MELEXIS AND GRAPHENEA ACCELERATE GRAPHENE BIOSENSOR DEVELOPMENT

Graphene Flagship partner Graphenea has joined forces with semiconductor company Melexis to accelerate the development of next-generation graphene biosensors. The collaboration focuses on evaluating Melexis' integrated GFET-on-CMOS platform, which combines graphene field-effect transistors with conventional semiconductor electronics to create highly sensitive and scalable biosensing systems. By merging Graphenea's expertise in graphene devices with Melexis' semiconductor integration capabilities, the initiative aims to move graphene biosensors from laboratory prototypes towards practical, deployable technologies.

The platform could enable compact and cost-effective diagnostic tools capable of detecting biomarkers for diseases such as cancer, neurological and infectious conditions, while also supporting environmental monitoring applications such as PFAS detection. By simplifying complex readout electronics and improving reliability and sensitivity, the collaboration represents an important step toward real-world graphene-based diagnostic systems and highlights the growing impact of the Graphene Flagship ecosystem in advancing biomedical sensing technologies.



What is the Graphene Flagship?

Bringing together 126 academic and industrial partners, 14 Partnering Projects and 53 Associated Members in 13 research and innovation projects and 1 coordination and support project, the Graphene Flagship initiative continues to advance Europe's strategic autonomy in technologies that rely on graphene and other 2D materials. The initiative, which builds on the previous 10-years of the Graphene Flagship, is funded by the European Commission's Horizon Europe research and innovation programme.

Visit graphene-flagship.eu

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WORK PACKAGE DISSEMINATION

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