GRAPHERGIA

Innovative pilot lines for sustainable graphene-based flexible and structural energy harvesting and storage devices

THE GRAPHERGIA PROJECT seeks to transform energy solutions with sustainable and efficient power technologies. It focuses on developing eco-friendly “dry-electrode” fabrication for energy storage devices, leveraging the potential of lasers in graphene synthesis. Through the development of a novel process for laser-assisted synthesis, functionalisation and integration of graphene materials into electrodes, GRAPHERGIA is paving the way for climate-neutral production of energy storage devices, with applications piloted in two key areas: energy-autonomous smart textiles and Li-ion batteries.

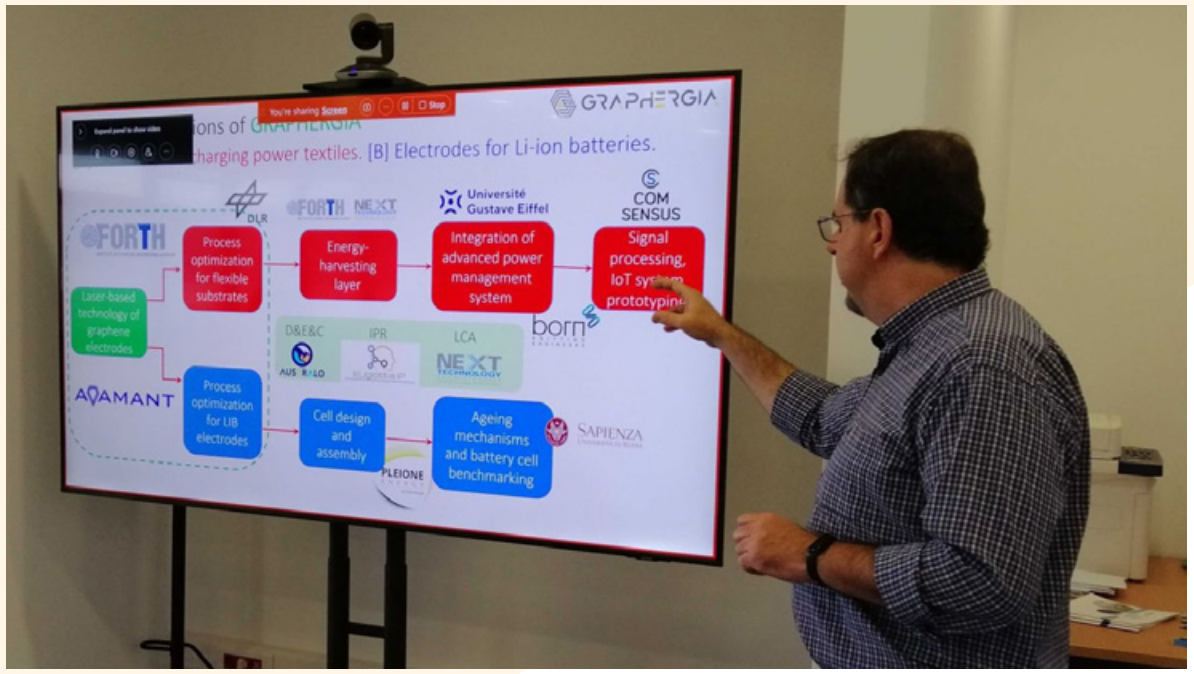
HIGHLIGHTS FROM 2024

The first year of the project focused on the establishment of key strategies for various areas including the research roadmap, the technical work packages (WP2 to WP6), the dissemination, communication and exploitation strategy and planning for scientific coordination and project management. By implementing concrete action plans and holding regular monitoring meetings, the GRAPHERGIA consortium promoted strong collaboration and achieved initial tangible results across the work packages. These efforts are paving the way toward the main goal of creating innovative pilot lines for sustainable graphene-based flexible and structural energy harvesting and storage devices.

> This year, GRAPHERGIA has advanced sustainable, laser-assisted graphene technologies for eco-friendly energy storage and flexible electronics. Looking ahead, we will focus on refining these innovative methods and showcasing their impact in key applications, such as energy-autonomous textiles and Li-ion battery anodes. GRAPHERGIA is not just about technological advancements but also about driving a greener and more energy-efficient future.”

Spyros Yannopoulos
Project Coordinator

GRAPHERGIA Overview of all WPs explained by Coordinator Spyros Yannopoulos. Credit: GRAPHERGIA team



GRAPHERGIA Team at Consortium Meeting in Prato. Credit: GRAPHERGIA team

Work Package 1
Work Package 1 is dedicated to Scientific Coordination and Project Management and is led by Spyros Yannopoulos from the Foundation for Research and Technology – Hellas (FORTH). This year, we established robust internal communication and collaboration channels and ensured effective project and data management. The project steering committee, gathering all work package leaders, convened every two months to monitor the progress of all work packages and to ensure synchronisation of the next steps across the various ongoing tasks. Also, the consortium met physically in the general assembly hosted in October 2024, by Next Technology Tecnotessile (NTT), in Prato, Italy.

In parallel, the coordination team facilitated GRAPHERGIA’s active involvement in the Graphene Flagship community, starting with participation in a joint kick-off meeting held in February 2024 in Gothenburg, Sweden, where four project partners attended. Additionally, the coordinator ensured that the different partners are involved in the Graphene Flagship dissemination, project management, road mapping and standardisation working groups. A significant achievement in this regard was successfully inviting the energy-related sister project, EMPHASIS[1], to join Graphene Flagship as a partnering project.

Finally, the project delivered two public reports under this work package: Deliverable 1.1 Project Management Plan[2] and Deliverable 1.2 Data Management Plan[3].

Work Package 2
Work Package 2: Design, Development, and Optimisation of Textile-Based TENGs and Micro-Flexible SCs, is led by the coordination team at FORTH.

During the first year of the project, FORTH focused on optimising the laser-assisted in-situ growth of graphene and graphene nanohybrids on various flexible substrates, including textiles. This effort led to the publication of one peer-reviewed paper[4] (closed access), with two additional manuscripts currently under review in high-impact journals. The method is now being further enhanced to accommodate various types of textile substrates relevant to the beneficiaries involved, particularly Born GmbH.

Specifically, during this first phase of the project, graphene oxide (GO) dispersions supplied by Graphenea, a partner of the GIANCE[5] project under the Graphene Flagship, were used as the graphene precursor. FORTH optimised a lab-scale process for the laser-assisted reduction of GO into high-quality graphene (LrGO) directly on textile surfaces. Building on this, the project partner ADAMANT undertook the upscaling of the process to parameters compatible with the roll-to-roll pilot line, which is expected to become operational in the final phase of the project.

Following this optimisation, a systematic evaluation of the laser-reduced GO (LrGO) electrodes will be carried out for applications in triboelectric nanogenerators (TENGs) and various supercapacitor configurations. Additionally, alternative cost-effective precursors for high-quality graphene production were investigated. Polyacrylonitrile (PAN) nanofibers, which can be easily and scalable produced over large areas through electrospinning, were shown to yield high-quality graphene with excellent conductivity after mid-IR laser irradiation. This material is currently under evaluation as an electrode for both TENGs and interdigitated (planar) supercapacitors. FORTH has successfully achieved uniform and conformal deposition of the energy-harvesting layer (various fluoropolymers) on graphene-coated textiles. The process took place using plasma-enhanced chemical vapour deposition (PE-CVD). The resulting materials have been thoroughly characterised in terms of thickness, stability, uniformity, surface energy, degree of cross-linking and breathability. Structural analysis and durability assessments are currently ongoing.

In parallel, inorganic carbide precursors, such as SiC, have been subjected to laser-assisted decomposition using two approaches: direct irradiation of a precoated layer of the SiC powders on current collectors (e.g., Cu foils) and the patented LEST technology developed by FORTH where the SiC materials was adhered to a transparent tape. This process successfully produced high-quality graphene structures decorated with Si and SiOx nanoparticles. These materials are currently under investigation as anode materials for Li-ion batteries.

The partners presented research work primarily related to WP2 to the scientific community at four scientific events, including two workshops. GRAPHERGIA’s results were disseminated at the following events:

At the ICOOPMA Conference – 10th International Conference on Optical, Optoelectronic and Photonic Materials and Applications, held in June 2024 in Pardubice (CZ), Prof. Yannopoulos delivered a lecture titled: *“Leveraging Laser-Assisted Techniques for High-Quality Graphene and Graphene-Based Nanohybrids in Energy Storage Applications”.*[6]

GRAPHERGIA 2024 Events Collage. Credit: GRAPHERGIA team

At the FLEPS Conference – International Conference on Flexible and Printable Sensors and Systems (an IEEE event), held in July 2024 in Tampere (FI), Prof. Yannopoulos and D. Hoxha were invited to present GRAPHERGIA's concepts and recent results at a Workshop co-organised by the ARMS project[7], titled *"Synergising Sustainability: Integrating Advanced Energy Storage with Harvesting for Wearable Electronics."*[8]

At the SSC 2024 Conference – 15th International Conference on Solid State Chemistry, held in September in Ústí nad labem (CZ), members from FORTH and DLR presented the latest advances of the GRAPHERGIA project at a workshop titled *"Electrochemical Energy Storage Materials and Processes"*. This workshop, hosted as a satellite event of SSC 2024 event, was co-organised by GRAPHERGIA and two other H2020 projects focused on electrochemical energy storage[9].

At the XXXVIII Panhellenic Conference on Solid State Physics & Materials Science, an event with international participation held in September 2024 in Ioannina (GR), Mrs. E. Amirali (then an undergraduate student, now a master's student supported by GRAPHERGIA) delivered an oral presentation on the preparation and characterisation of PAN-based laser-derived graphene[10].

The project achieved significant progress in WP2, optimising the laser-assisted production of graphene-based materials on textiles and various flexible substrates. Looking ahead, the focus will be on further optimising these processes and integrating them into functional devices, ensuring their successful implementation in the project's two demonstrators: self-charging, energy autonomous textiles and anodes for Li-ion batteries.

Work Package 3
Work Package 3 focuses on the design and assembly of Li-ion battery (LIB) cells, with an emphasis on preparing laser-scribed graphene-based anodes. This work package is led by Pleione Energy GmbH (PLE).

The primary scientific objectives of WP3 are to design LIB cells incorporating anodes made from laser-synthesised graphene-related materials, investigate the ageing mechanisms of graphene-based LIB cells and establish benchmarks for their performance. These goals are addressed through four tasks, with two of them initiated during the first year of the project. Task 3.1, *"Cell Design of Graphene-Based Anode Materials,"* commenced in March 2024 (M6), while Task 3.2, *"Graphene-Based Battery Assembly and Performance Evaluation,"* started in July 2024.

In the past period, the focus was on designing graphene-based anode cells and conducting preliminary experiments on coating SiC powders of various sizes and film thicknesses onto copper foil. These coatings were decomposed using different types of lasers to prepare anodes based on 3D graphene structures decorated with Si and SiOx nanoparticles. Alternatively, the LEST method was employed to simultaneously synthesise and deposit such 3D graphene films onto Cu current collectors. The primary goal was to initiate the development of the battery manufacturing process and evaluate the performance of the resulting anode materials.

Currently, University Sapienza Rome (URM) and FORTH are defining the next steps to utilise Kerr-gated Raman spectroscopy and Impulsive Transient Reflectivity spectroscopy (developed by URM). These advanced techniques aim to provide critical insights into the state of charge of graphene and graphene/nanohybrid electrodes, as well as to understand the electron/phonon coupling between graphene layers and the nanoparticles decorating them.

Additionally, in this context, URM took a leading role in organising and hosting the 28th International Conference on Raman Spectroscopy (ICORS 2024[11]), where GRAPHERGIA was prominently featured as a Flagship ongoing research initiative, showcasing its advancements and contributions to the field.

Work Package 4
Work Package 4 is focused on advanced electrical modelling and efficient power management of Tribo-Electric Nanogenerators (TENGs) for energy harvesting and self-powered sensing Internet of Things (IoT) applications and is led by Université Gustave Eiffel / ESYCOM lab (UGE).

During the first year, activities focused on the design and development of conditioning circuits for TENG rectification (Task 4.1). Specifically, UGE developed theoretical models to establish a strategy for selecting the optimal unstable charge-pump conditioning circuit for a given TENG, based on specific mechanical excitation parameters and the maximum allowable voltage in the system. This theoretical approach was validated through simulations. In parallel, the automatic test bench for characterising a gap-closing TENG – a modelled as a voltage source in series with a variable capacitor – was successfully finalised.

The leading partner, UGE, presented the ongoing WP4 research at three scientific events, including the symposia/workshops (a) "Self-Powered Sensors Based on Nanogenerators" at the European Materials Research Society (e-MRS) 2024 Spring Meeting[12], (b) Materials Challenges in Alternative and Renewable Energy 2024 (MCARE'24)[13] and (c) PowerMEMS+ 2024: Micro and Miniature Power Systems, Self-Powered Sensors and Energy Autonomous Devices[14].

Work Package 5
Work Package 5 focuses on the design, manufacturing, and testing of representative technology demonstrators and is led by ADAMANT Composites Ltd. (ADA). It started in February 2024. During this period, efforts were concentrated on early eco-design analysis and the optimisation of critical parameters for the technology demonstrators (Task 5.1 led by NTT). This task serves as the foundation for ensuring that the design and development processes align with eco-design principles, supporting the overarching objective of minimising environmental impact across the entire product life cycle.

The key activities have included a literature review and an evaluation of eco-design practices relevant to the demonstrators, as well as an assessment of European legislation on eco-design, circularity and carbon neutrality goals. This research will be continuously updated and refined as the partners developing the demonstrators provide more specific information. Furthermore, the eco-design analysis will be closely integrated with the materials, components and processes associated with each demonstrator, which will be addressed in later stages starting in March 2026. This collaborative approach will facilitate the identification of the most appropriate eco-design strategies and regulatory frameworks to ensure compliance and sustainability.

This work package also ensures alignment with European legislation and monitors the evolving regulatory landscape, including the Eco-design for Sustainable Products Regulation (ESPR). This alignment is essential for defining the eco-design criteria for the demonstrators as the project advances. During the first year, the focus was on establishing a solid foundation for future activities by conducting essential eco-design evaluations and preparing for more detailed work in the later stages of the project.

Work Package 6
Work Package 6 is dedicated to Life Cycle Assessment, Sustainability and Eco-design Approach, and is coordinated by Next Technology Tecnotessile (NTT).Over the past 12 months, efforts have focused on introducing and engaging the GRAPHERGIA team with sustainability and eco-design concepts, which will be implemented as a comprehensive approach throughout the project's research activities.

The applied Life Cycle Assessment (LCA) methodology was outlined in detail during dedicated online meetings, covering the four key steps defined in ISO 14040. This LCA approach was integrated with the Life Cycle Costing (LCC) methodology, which evaluates all costs incurred throughout a product's lifetime, work or service. The LCC methodology was also introduced to GRAPHERGIA partners during webinars, where strategies for assessing both direct and indirect costs of the developed products were discussed.

In parallel, partners initiated a preliminary Social Life Cycle Assessment (S-LCA) survey to gather feedback from involved stakeholders. Additionally, the eco-design methodology, which will guide the development of components and products during the project, was presented in online meetings to ensure its seamless integration into the project's implementation.

Work Package 7
The last work package focuses on the dissemination, exploitation and communication of project results. The leading partner is AUSTRALO Marketing Lab (AUS).

The first year has been highly productive in terms of communication and dissemination activities. The project has evolved from a concept on paper into an active initiative with attractive branding, actively engaging European and international research and innovation communities across different channels and stakeholder events.

The first step was to create GRAPHERGIA's branding, which enabled it to be identified among other related projects, especially the Graphene Flagship Initiative. A solid strategy guiding all communication, dissemination and exploitation activities throughout the project was also established. The communication activities have focused on sharing updates and knowledge from the project; the GRAPHERGIA website and social media channels are essential tools for communication. The dissemination activities aim to enable stakeholders to use GRAPHERGIA's research results effectively. This includes participation in various events, the submission of scientific publications, and the publication of non-sensitive project results, which are essential for dissemination. In parallel, the partners have been engaged in the implementation of the exploitation strategy and especially the first exploitation workshops, to reflect the key exploitable outcomes and the value proposition of GRAPHERGIA. In addition, deliverable 7.1[15], a public report outlining the impact strategy to be implemented throughout the project, was submitted.

Current and future actions aim to promote active stakeholder participation through targeted channels, increasing visibility and establishing a robust network of stakeholders around the GRAPHERGIA project. This approach will enhance sustainability and facilitate the market uptake of the key exploitable results achieved through GRAPHERGIA.

DISSEMINATION AND EXPLOITATION

GRAPHERGIA members have shown a strong commitment to the project, united by shared objectives and a cohesive visual branding identity. This collaboration has resulted in the development of a growing network of stakeholders, the GRAPHERGIA hub, 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 its first year, GRAPHERGIA effectively communicated its main activities and results through targeted channels, including social media platforms, where it has garnered over 1,400 followers (LinkedIn, X and BlueSky), a bi-annual newsletter[16] with almost 500 subscribers and the project website (graphergia.eu), which features over 40 blog articles highlighting project updates and news. Finally, the project launched its first video[17] played for the first time at the Graphene Week 2024.

Regarding dissemination, the team has presented GRAPHERGIA's ongoing research at 11 scientific events across Europe and submitted a few scientific publications to peer reviewed journals.

GRAPHERGIA partners hosted three joint scientific workshops engaging the research community in the Graphene Flagship and beyond, gathering around 190 participants in total.