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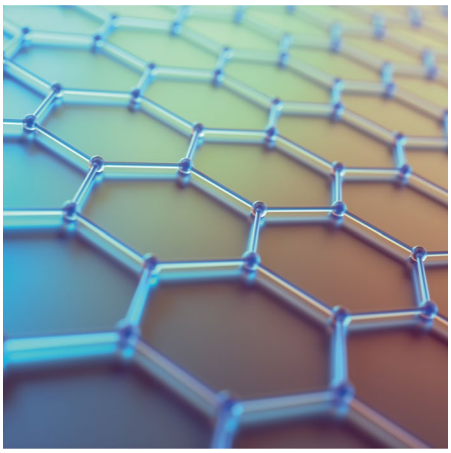
A mixed legacy

After a decade of intense activity, the Graphene Flagship has helped to establish an incipient European graphene industry, yet mainstream commercialization of graphene products continues to be hindered by limited market readiness and industry acceptance.

In the autumn of 2013, with a budget of €1 billion and 10 years to make the most of it, the Graphene Flagship took its first steps[1]. The flagship's ambitions were clear: to turn early-stage discoveries into new products and technologies and to capitalize on Europe's expertise to enable job creation driven by an emerging graphene technology[2]. The goal of reaching commercial markets was not an aspiration solely supported by graphene's properties but backed up by nearly a decade of work when numerous promising prototypes such as flexible touchscreens, photovoltaic cells and water-filtration membranes were demonstrated, and research publications showcased graphene's potential for optoelectronic devices, batteries or biotechnologies. The flagship's focus expanded beyond graphene; a whole family of atomically thin two-dimensional (2D) materials was emerging with diverse properties that could be stacked layer-by-layer to form heterostructures with tunable functionalities. With great potential in diverse and timely applications, the flagship consortium believed it was time to bring graphene technologies out of the research labs and into the limelight.

But the launch of the flagship also attracted criticism. First, the Graphene Flagship, launched along with the Human Brain Project, was one of the two initial large-scale Future and Emerging Technologies initiatives and many questioned whether the concentration of research funding in such megaprojects was the best strategy to capitalize on Europe's research output. Second, in the absence of a clear, unique 'killer application' for graphene-based technologies, the flagship's return-on-investment potential was doubted. To deliver on the flagship's promise, graphene technologies needed to overcome critical technical challenges such as scaling-up production and drastically reducing production



costs while maintaining the highest material quality. This was an essential minimum entry requirement for graphene-enabled devices to be considered as potential alternatives to traditional semiconductors in the electronic and photonic industries where they have been proposed, for example, to replace indium tin oxide as transparent conducting electrodes on touchscreens and wearable electronics, or even to replace or enhance silicon chips in the semiconductor industry.

A decade has passed, and later this year the Graphene Flagship is coming to a close. In the Q&A in this issue of *Nature Materials*, Jari Kinaret, Director of the Graphene Flagship, discusses the achievements of the consortium and looks ahead to future graphene research initiatives within Europe. The Graphene Flagship has been successful in securing industrial engagement, with roughly 50% of the consortium consisting of companies, and the flagship itself has launched 17 new companies and more than 100 graphene-related products. Concrete efforts towards improving scalability, reproducibility and material quality, such as the launch of the 2D Experimental Pilot Line in 2021 (ref. 3), are bringing tangible progress on taking electronic and photonic devices out of the lab. Kinaret further outlines how the European Commission will continue to support the activities initiated within the flagship under the Horizon Europe scheme.

However, despite progress, graphene is yet to make a dent in the consumer markets. A killer application hasn't yet been identified and interest in some of the initially promising applications has faded over time. Moreover, even when credible graphene applications seem to be ready for the consumer market and seemingly capable of outperforming competing technologies, uptake by the relevant end-use markets remains anecdotal and their societal impact negligible. The global graphene market volume, although steadily growing, has been consistently in the lower range of earlier forecasts[4]. It is promising that, fuelled by the Asia Pacific push, market growth is forecasted to pick up the pace in the coming decade, but the global graphene industry is still heavily reliant on public and private funding and companies are struggling to generate a profit[4]. The recently announced European Chips Act[5] and the UK National Semiconductor Strategy[6] will consider graphene-enabled alternatives to traditional semiconductor 2D materials, but it is hard to envisage 2D materials having an impact in the semiconductor industry beyond few niche applications in the near future.

The Graphene Flagship has been successful in setting the foundations for a graphene industry in Europe. Success stories such as the development of a graphene-based air-filtration system in a partnership including Airbus and Lufthansa provided a glimpse of graphene's commercialization potential, while start-ups such as Inbrain — who develop graphene-based brain implants to treat patients with neuronal disorders — indicate further prospects for graphene technologies. However, the role and scale of impact that graphene technologies may have in the advancement of society in the short- to mid-term remains unclear. Still, the continuing support from the European Commission and the flow of fundamental studies from research labs are reminders of the exciting prospects of fully harnessing the properties of 2D materials.

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