Graphene is on track to deliver on its promises

Fifteen years since the ground-breaking experiments on graphene, its commercial exploitation is progressing at the expected pace for a new material.

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Bringing a new material to market has the potential to shift entire industries. What is often forgotten is that it takes years until science-based innovations translate into commercial activities, and at least 20 to 30 years until significant market success is achieved[1,2]. This has already happened for very different materials and devices, such as immobilized enzymes, heat transfer materials, conducting polymers or lasers for manufacturing, to cite a few[1,2].

Bringing a new material to market is not without its challenges and, in this day and age, people seem to assume that materials development can be as quick as software development, which is clearly not the case. Innovation based on new materials is hard, long and expensive, and often it does not come to final fruition.

Time to market might even span centuries. There were 124 years between the discovery of Si in 1824[3] and the creation of the Si chip in 1958[4]. Now, chip technology is used in almost all modern products. Trillions of dollars have been invested in semiconductor technology since the first device in 1947. Development of a new node in the International Technology Roadmap for Semiconductors (ITRS) for transistors with shorter channel length is a multibillion dollar investment for a single company and, if successful, the establishment of a fab requires a further multibillion dollar cash injection[5]. It is also interesting to note that, for the first 7 years after 1947, the devices were based on Ge, before a switch to Si happened[4], thanks to the pioneering work on Si itself by Teal and colleagues at Bell Labs and Texas Instruments[4].

Innovation does not evolve in a vacuum. It does not proceed in a linear way from basic to applied research, to development, design, production and marketing. Rather, it is characterized by a broad variety of linkages, interactions and feedbacks between a diverse set of actors and activities. Innovation can be perceived as a systemic process[6,7]. Thus, establishing efficient networks between academia and industry, and fostering a co-creation cycle to manage early technological risks, are key drivers of innovation. This holds true in particular for innovation based on new materials[1], such as graphene and related materials (GRMs), including non-carbon-based layered materials and their heterostructures. Materials based innovation is characterized by a decoupling of materials research development and value creation at the back end of the value chain by system integrators and original equipment manufacturers[8]. In addition, frequently only small amounts of material are needed in final products, creating additional challenges for materials producers to set up viable business models. For example, a 300-mm graphene wafer has less than 0.1 mg of graphene, and can contain thousands of devices. Similarly, in a polymer composite, inclusion of just a few volume percent of graphene can result in orders of magnitude increases in electrical conductivity, and over 100% improvement of mechanical properties[9]. The graphene industry is thus a good example illustrating the issue. Nevertheless, new materials as enablers play a key role for the sustainable transformation of many important industries, such as energy, machinery, automotive and medical devices[8].

Facing this scale of a challenge, the early innovation work is heavily dependent on support actions, typically backed by public funding, before industry and venture capital can catch the ball. For example, in the case of transistors, early development was heavily dependent on public funding[4]. In the case of GRMs, the European Graphene Flagship and similar initiatives in China, Korea, USA and Japan play this role.

Innovation support actions facilitate the creation of an innovation ecosystem, which helps to overcome the challenges. Such actions are most efficient if implemented in line with research and innovation initiatives. These include a comprehensive set of services ranging from a macro (whole sector) to a micro (firm level) perspective. A key requirement is the identification and characterization of strategic target areas for innovation via technology and innovation roadmaps, such as the ITRS for Si and the GRM roadmaps[9]. Information on markets is an important ingredient to define the technical requirements for such roadmaps.

In the case of graphene, a number of market studies are available, with a broad range of market value estimations, ranging from ~US$180 million[10] to US$2.1 billion[11] in 2025. In order to find out common trends, we consider 20 market studies published between 2013 and 2019[10–29] and consolidate them to a meta-market analysis. Overall, they predict a strong growth with an average growth rate of approximately 40% up to 2025, as derived from the slope of the data in Fig. 1a. This also shows a global market demand ranging from ~US$15–50 million in 2015 to ~US$200–2,000 million around 2025.

We note that in these market studies it is often not clearly stated what exactly the numbers refer to. In most cases, they state 'global graphene market' and give the numbers in US dollars. Often, they refer to it as the revenue (but not always). In some cases, they talk about the 'market value of graphene'. Here, we assume that these numbers represent the revenue that is made with the material itself, not with the final product. This is quite important since the revenue for Si-based devices is orders of magnitude higher than that from bulk Si sales. For example, in 2018 the total market for Si wafers was US$9 billion[30], while the smart phone global sales enabled by Si chips exceeded ~US$500 billion[31]. Assuming a similar ratio, the total market value for graphene-enabled products should be a factor ~100 larger than in Fig. 1.The other question is how are the numbers derived in these market studies. Every provider has its own (more or less confidential) way to estimate them. In most cases, they are based on current market prices of the producers, production volumes of the producers, and estimations from experts and producers. Most providers claim to do extensive background research and many conduct phone (or personal) interviews with key players. Unfortunately, we cannot assess the validity of these approaches.

Thus: (1) we assume the numbers represent the value/revenue of the graphene material, not the end product that contains graphene; (2) we assume the numbers are calculated/estimated by mapping the (ideally) whole graphene production sector, the current prices and production volumes, talking to (ideally) all relevant players in the field; and (3) we need to accept that these are estimates, and that we cannot know how accurate they are.

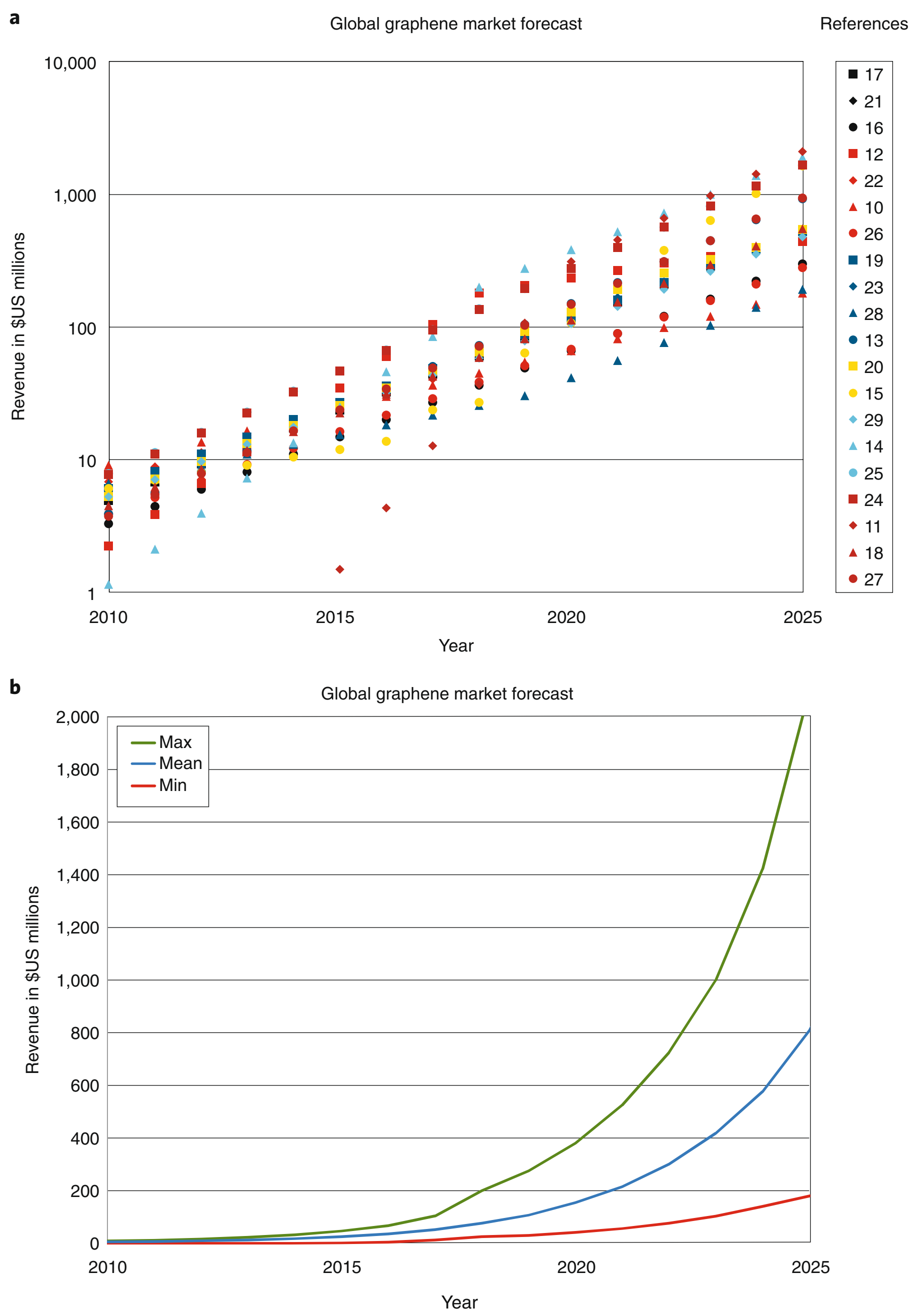

Fig. 1 | Historic and predicted revenue of the global graphene market. a, Data from individual market studies. **b**, Minimum, maximum and mean revenue. Data sourced from refs. [11–30].

The applications for graphene are manifold[9]. While some are close to market entry, or have entered the market already, such as composites and paints, others will need more time and research and development (R&D) efforts. In order to evaluate the potential of graphene in different applications, we compare the market forecasts by application for the year 2025[15,19,23,28]. Figure 2 plots the compound annual growth rate (CAGR) as a function of predicted revenue for different application areas. Most predictions agree on a very high (>US$100 million) market potential of energy storage applications (yellow squares), such as batteries and supercapacitors. Graphene composites and conductive films/electrodes (blue squares) are predicted to have high (~30%) CAGR and high revenues, whereas graphene-based (opto)electronics and sensors (grey squares) are expected to have high (>20%) growth rates, but no large revenue yet. Graphene R&D (black squares) is expected to continue at a constant CAGR of approximately 0%, as more and more products enter the market, which might indicate that in some fields graphene is already beyond the mere R&D phase.

An important issue is creating trust and confidence, with recognized suppliers of graphene, in order to reduce uncertainty among the industry players. There is thus an ever-increasing need to provide trusted validation and standardization services for GRMs, as important innovation support actions. Support acceptability of GRM-based innovation in society is another important issue. Impact assessments of health and safety, validation services and international standards are suitable means to this end.

The strategic information on the promising application areas shown in Fig. 2 needs to be translated into concrete innovation actions at a product and device level.

We have identified several tens of graphene-based devices or prototypes already in the market or close to commercialization in Europe. Most are related to the production of the material or intermediates. These include systems for cost-effective and large-scale production of GRMs[32]. Components and systems exploiting graphene are also reaching the market. These include, for example, graphene photodetectors with low noise over a broad spectral range from visible (400 nm) to near infrared/short-wave infrared (1800 nm)[33], Hall-effect sensors[34], and graphene-enhanced composites for the leading edge of aeroplanes' horizontal tails, allowing weight reduction and fuel savings[35]. Corrosion-resistant graphene-reinforced resins are already in use in chemical plants, replacing metals, thereby saving cost and weight[36]. Tens of new start-ups and spin offs have been already created in Europe. Worldwide, orders of magnitude more are present. For example, in China thousands of companies claim to be commercializing graphene. However, we are entering the time of mergers and acquisitions and many such companies will not survive or will be consolidated. Only companies following recognized standardization and validation, and health and safety procedures will survive in the long run.

It is not enough to use the word graphene to claim a novelty of a product. As a matter of fact, most 'graphene' producers sell materials little, if anything, related to ideal graphene[37]. This does not mean that, unless a single perfect monolayer of graphene is used, one should not claim the product is based on graphene. It simply means that producers should be open and clearly specify what they employ. Huge opportunities exist for graphene

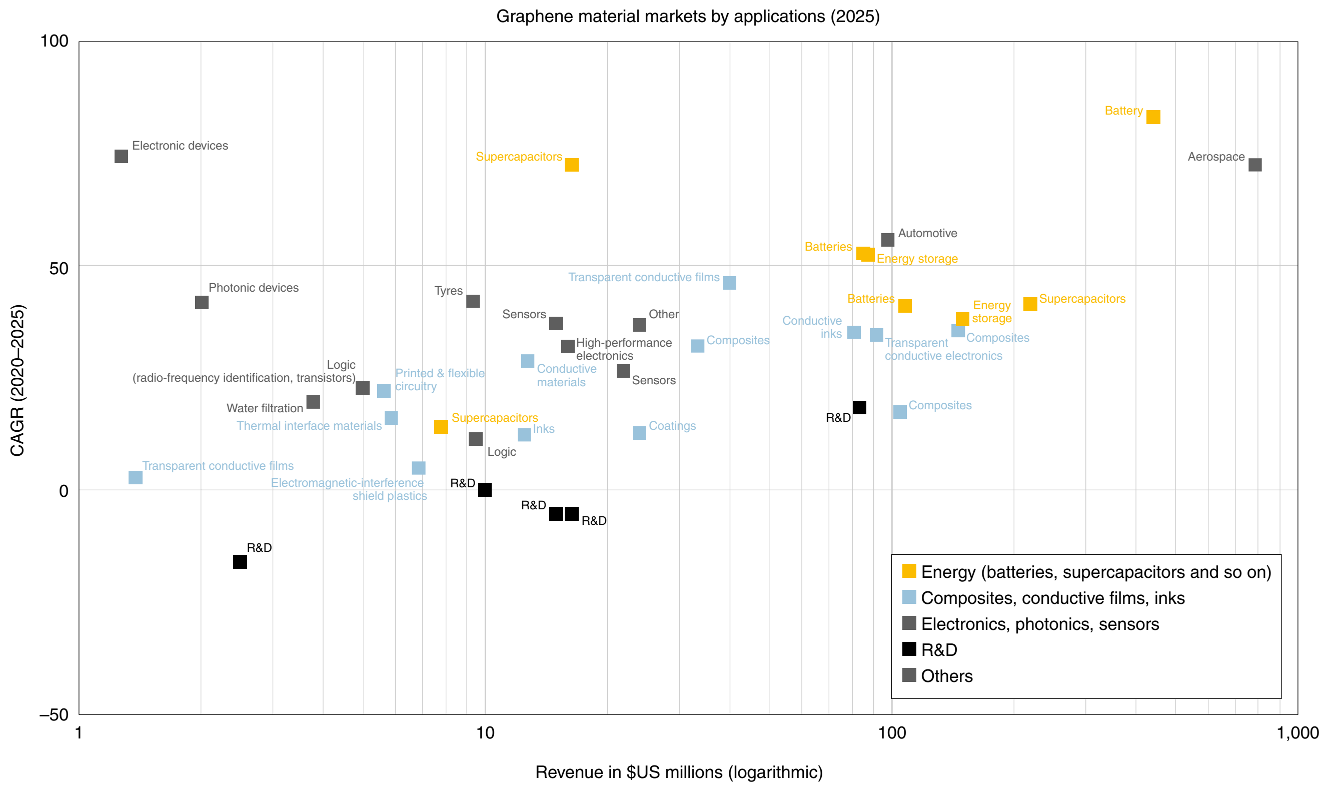

Fig. 2 | Graphene markets by application by 2025. Revenues and CAGR as predicted comparing the data in refs. [15,19,23,28].

oxide, defective or functionalized graphene, powders or inks containing thick multi-layer flakes and so on. One should not be snobbish about this. Claiming otherwise is unnecessary and conceptually wrong. What is needed is for a clear identification of the products to be provided by suppliers. Original equipment manufacturers may not want or need to reveal the type of GRM present in their devices. For users, what matters is not how many layers of graphene are present, but if such devices satisfy their needs, being cheaper, multifunctional, or generally outperforming previous and competing technology. However, if producers want to stay in the market they must build trust for reproducible and fully characterized material, whatever the specific composition, and not over claim, or use 'graphene' as a trademark with no real meaning.

The final performance of GRM-based devices needs to be significantly better than existing technology. While in fields like composites or inks, improvements of the order of several percent are already interesting, in (opto)electronics orders of magnitude higher performances are expected before a device can be considered competitive with respect to standard technology.

It is crucial to keep in mind Kroemer's Lemma of New Technology: the principal applications of any sufficiently new and innovative technology always have been, and will continue to be, those created by that technology. This means that the most promising areas for GRM applications are not those where GRMs provide incremental improvements with respect to existing technology, but new areas enabled by GRMs themselves, otherwise not possible. For example, the massless Dirac fermions in graphene make it an ideal material for optoelectronics, allowing broadband, high speed and low power consumption[38,39]. This makes graphene suited to create new devices with performances not allowed by existing semiconductor technologies. On the other hand, producing a GRM-based transistor with lab performance even 10 times better than current commercial devices is no guarantee for final uptake, unless truly novel properties, not attainable with current technology, are implemented. For example, a device with low logic performance, but that is bendable, stretchable and washable — unlike normal Si-based chips — could open significant markets in food packaging and textiles.

For the future route of graphene towards industrialization we expect short-term (<5 years) applications in the materials sector (for example, composites, inks and coatings), and in the mid-term (5–10 years) in the energy sector (for example, batteries and solar cells) and in optoelectronics (for example, optical switches and modulators for 5G networks, and sensors). In the next 5–15 years, these applications will further diffuse into markets. Construction materials with improved properties, membranes for water purification, electrodes for supercapacitors, flexible solar cells, sensors for the internet of things and autonomous driving will benefit from graphene to realize their market potential. In the long-term (~15–30 years) we will also see medical devices taking advantage of graphene's properties, while layered materials are a new platform for quantum technology[40].

Fifteen years after the ground-breaking work on graphene, expecting broad market penetration is not realistic. Graphene certainly has unique properties. However, it is not different from other new materials, which need at least 30 years and large investments to generate substantial market impact. Creating an innovation ecosystem and providing holistic innovation support are key factors facilitating commercialization. Nevertheless, first applications have already reached the market and market forecasts are promising. There are many graphene-based innovations expected in the next 15 years. When it comes to layered materials and heterostructures we expect a similar pattern as graphene to be repeated, but shifted forward in time, since many of these are still in the early stages of fundamental research, and commercially viable mass or large-area production approaches are just beginning to emerge. ❒

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