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RECEIVED
31 July 2020

REVISED
21 December 2020

ACCEPTED FOR PUBLICATION
20 January 2021

PUBLISHED
18 February 2021

TOPICAL REVIEW

Graphene Roadmap Briefs (No. 1): innovation interfaces of the Graphene Flagship

Henning Döscher and Thomas Reiss

Competence Center Emerging Technologies, Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe, Germany

E-mail: henning.doescher@isi.fraunhofer.de

Keywords: graphene and related materials, innovation roadmap, industrialization

Abstract

Graphene and related materials (GRMs) promise ample impact on future industries. In the frame of the Graphene Flagship project, its technology and innovation roadmap (TIR) process explores pathways towards GRM industrialization. The initial issue of Graphene Roadmap Briefs outlines scope and goals of the novel format in the context the history, present status, and projected future of the TIR process. It particularly focusses the novel innovation interface investigation (3I) approach designed to explore the impact of GRM on the formation and transformation of potential future value chains. Context specific innovation spheres and their interrelations through innovation interfaces constitute the underlying key concepts of the 3I approach and serve as essential building blocks of prospective supply chains. The practical implementation of 3I studies bases on an extensive stakeholder consultation strategy to aggregate all relevant perspectives from key experts along a specific innovation chain. Each study culminates in an interactive 3I focus workshop to consolidate consensus expectations. An explorative innovation roadmap summarizes the joint vision for the innovation under investigation and outlines a realistic pathway for its implementation. We conclude with a course overview on earlier TIR results, on recent focus topics, and on the selection process that shape the current status and the future trajectory of the TIR process within and beyond the Graphene Flagship.

About: Graphene Roadmap Briefs

Graphene Roadmap Briefs highlight key innovation areas impacted by graphene and related 2D materials (GRMs) as well as overarching aspects of GRM innovation status and prospects. The series bases on the evolving technology and innovation roadmap process initiated by the European Graphene Flagship. It covers crucial innovation trends beyond fundamental scientific discovery and applied research on GRM utilization opportunities.

List of acronyms

GRMs	graphene and related 2D materials
TIR	technology and innovation roadmap
3I	innovation interface investigation
S&T	scientific and technological
STI	science, technology, and innovation
IS	innovation system
TIS	technological innovation system
MIS	material innovation system
MLP	multi-level perspective
I/O	input and output
SWOT	strengths, weaknesses, opportunities, and threats
USP	unique selling proposition
KPI	key performance indicator
TRL	technology readiness level
OEM	original equipment manufacturer

The list of abbreviations and acronyms excludes proper names, common use (such as 2D), metric system units, chemical symbols, and isolated introductions (for terms most common as acronym such as NGO or CNT).

1. The technology and innovation roadmap process

The practical isolation of graphene in 2004 [1] sparked enormous expectations in terms of scientific discovery, technological application opportunity, and potential economic value. Properties, that merely existed in theoretical concepts [2] before, suddenly materialized. Long sustained growth in both scientific publication and patent application records (compare figure 7 below) based on GRMs evidence significant momentum sometimes seen as hype [3]. Of course, the translation of a novel material into widespread economic impact takes substantial time spans [4] and present market developments appear to lag behind initial expectations. Roadmaps provide a mechanism to aggregate the foresight of key experts and, thus, guidance to the greater community of potential stakeholders.

1.1. Roadmapping in context of the Graphene Flagship

The evolutionary development of the graphene TIR process is deeply entangled with the European Graphene Flagship. Both root back to the early 2010 years, when the European 2D material research community came together to turn the hype momentum in the wake of the 2010 physics Nobel prize [5] into a longer lasting research and development agenda. In 2011, leading scientists received a preparatory seed grant [6] for the then novel EU Flagship mechanism. By 2012, they had aggregated their joint visions in an S&T roadmap [6]. It created the foundation for both the Graphene Flagship proposal [7] and the 2015S&T roadmap publication [8].

The Graphene Flagship consortium began its work in 2013 and launched a competitive call [9] to design and implement a mechanism for regular roadmap updates. Based on our successful offer, Fraunhofer ISI joined the project consortium in 2014. Our approach includes the integration of market and innovation perspectives (see below) that drive our implementation of the TIR process of the Graphene Flagship ever since.

Figure 1 summarizes the different phases of the roadmap process in context of the Graphene Flagship. Its preparation process triggered intense exchange between numerous key scientists resulting in the initial S&T roadmap of 2012 [6] and its refined publication in 2015 [8] (in orange). In parallel, the second phase the roadmap process (in yellow) started in 2014, when the Graphene Flagship assigned us with the mission to add market perspective covering the full breadth of conceivable applications of GRMs as identified by the scientists. We engaged in numerous interviews with experts from industry and the Graphene Flagship, before organizing two large portfolio assessment workshops in 2016. The gathered insights also formed the foundation for 31 subject-specific roadmaps covering promising fields for GRM applications. Our full STI roadmap report [10] was fed back into the Graphene Flagship in 2017 where it informed the planning process of subsequent project phases. The dedicated Graphene Flagship roadmap website [11] now showcases selected content from the STI report, while key scientists currently work on refining its science domain sections for its full publication as successor of the comprehensive roadmap published in 2015.

In 2017, our team entered into the third phase of the TIR process (in magenta) that persists today. The goal shifted towards further depth of analysis, in particular regarding opportunities and bottlenecks for wider diffusion of GRM-based innovations. With the realization that market peculiarities in no way stop at the level of primary GRM application fields, but further branch out with their downstream utilization, typically over several aggregation steps to highly complex end products. The intended depth thus practically forbade complete in-breadth coverage of the full diversity of GRM application.

Instead, we decided to focus on very specific utilization scenarios including the full path towards final products. We developed the 3I mechanism to implement this value chain based approach. Here, we introduce the underlying conceptual framework (chapter 2) and discuss its practical implementation in the Graphene Flagship (chapter 3). The full portfolio of GRM applications (chapter 4) as assessed in 2016 formed a solid starting point for the selection of most relevant focus topics (chapter 5). We begin with a brief discussion of our general TIR scope and approach in the context of other roadmap work in the GRM field and the intended function for the Graphene Roadmap Brief series.

1.2. TIR approach and goals: from science to innovation

Initiated by the European Graphene Flagship, the TIR process aims to guide the community towards the development of products based on graphene, related (2D) materials, and hybrid systems (GRM). The TIR goal is outlining the principle rules to develop the GRM knowledge base, the means of production and development of new devices, aiming at a final integration of GRM into systems. These objectives address three main target groups: (a) the internal Graphene Flagship community; (b) external research communities; and (c) industry—which shall be supported in recognizing the potentials of GRM for future applications. In that sense, the graphene TIR aggregates a common view on GRM and provides guidance for graphene research towards market demands. In particular, the TIR offers strategic guidance for both the Graphene Flagship and the industrial uptake of GRM.

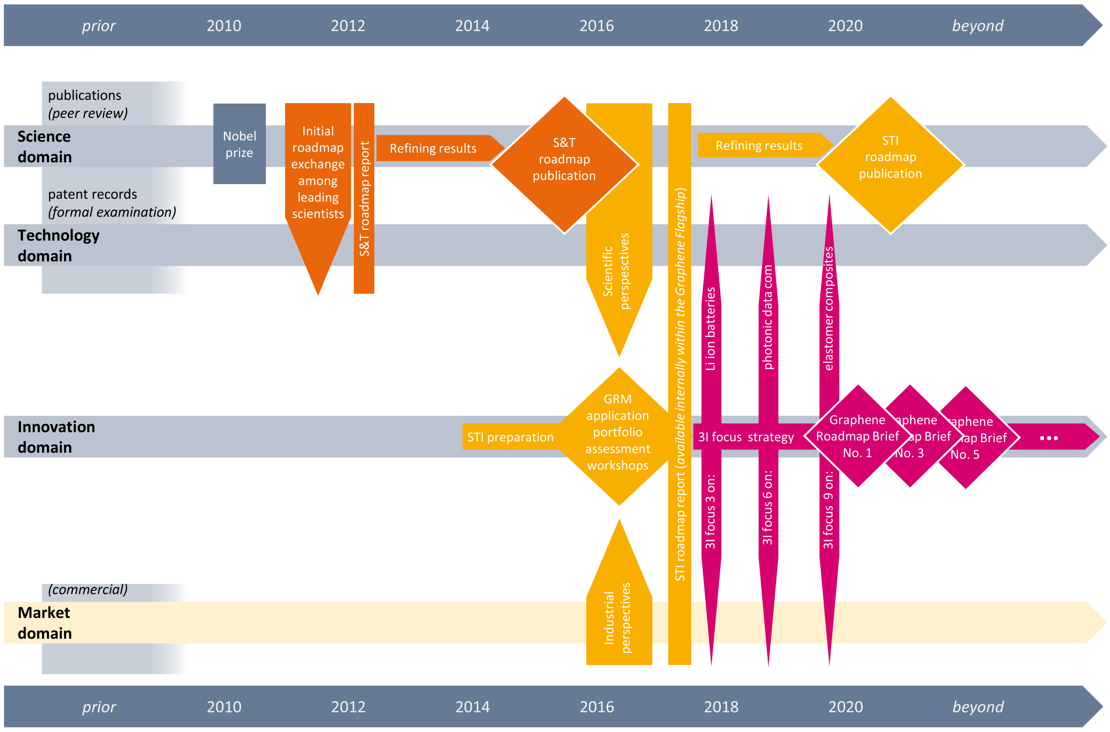

Figure 1. Historic technology and innovation roadmap context for graphene and related materials in the Graphene Flagship and beyond.

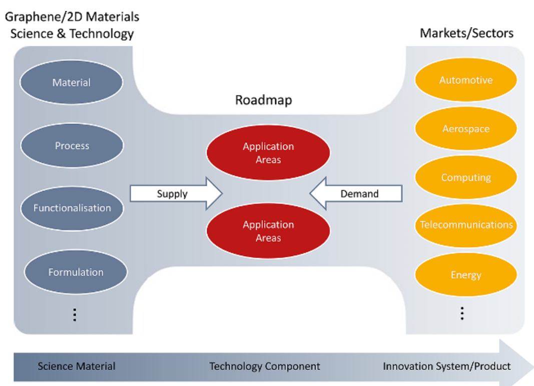

Figure 2. Fusion approach with technology supply on the one hand and markets/sector demand on the other, both meet in broad application areas that structured earlier TIR reports.

Figure 2 illustrates the general fusion approach that forms the underlying principle for the entire TIR process. It complements the traditional S&T roadmapping with market-side intelligence on industrial needs. The former (on the left, in blue) aggregates present and future technology offers enabled by GRM, while the latter compiles insights from relevant markets and sectors (on the right, in yellow) that potentially require novel solutions for certain practical needs.

In this context, innovation research distinguishes between 'technology push' and 'market pull' [12], which essentially reflect the supply of and demand for novel technology. Often, both sides only interact by coincidence, despite their alignment constitutes a crucial success factor that determines the innovation impact. Our fusion approach (in the middle, in red) intends to bridge that gap and, thus, match technology development enabled or enhanced by GRM with industrial market need.

In a first step, we identified four overarching application areas (see chapter 4 for brief descriptions) where applied GRM research and industrial interests may overlap. Their definitions remained coarse enough to comprehend the full diversity of GRM applications, but still helped to structure earlier roadmap reports and guide their readers. At the highest aggregation level, figure 8 below visualizes the most promising GRM application fields for each area according to our 2016 analysis. The fusion approach (figure 2) already foreshadowed value chain context when identifying STI domains with material, component, and system production levels.

However, we had to widen our scope significantly to achieve advanced depth of analysis. In practice, the crucial gap between the supply of and the demand for novel technical solutions may replicate multiple times along practically existing or potential future value chains.

Figure 3 depicts a highly generalized value chain that consists of those three fundamental levels of materials supply (light blue), component production (light red), and systems integration (light yellow) mentioned before. However, their identification with STI domains may be misleading as all the above co-exist in different shapes and forms at each given step

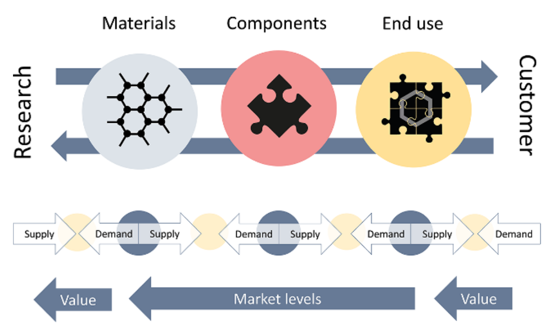

Figure 3. Sketch of the generalized value chain based approach for in-depth TIR research following the novel 3I scheme.

along any practical value chain. In particular, viable industrial actors cover each single step of the supply chain once a value chain matures.

Independent entities often specialize in a certain value addition step, but also sub-units of vertically integrated corporations may fulfill that function. When novel materials and technologies emerge, start-ups and university spin-outs may be the first actors on early markets. On an abstract level, all commercial stakeholders of readily existing and emerging value chains share the desire to expedite their very own business. In particular, they usually seek to advance their production towards the ability to offer higher value to their downstream customers. Upstream innovations usually only spark interest according to their capacity to enable advanced products and/or cost reductions.

GRM rarely offer any direct economic value by themselves, but they hold outstanding promise as enabling factor for novel or advanced secondary technologies that may (or may not) impact virtually any economic sector. Along the way, the crucial gap between supply of and demand for novel technology as visualized in our fusion approach (figure 2) essentially breaks down into multitude of more specific replicates, which may form structuring elements for potential future value chains enabled by GRM (figure 3). This series of gaps between technology supply and demand explicitly includes the translation of (a) fundamental GRM research (on discovery and synthesis of materials) into commercially sustainable production, (b) applied GRM research (in specific application fields) into mass production, but also (c) research and development at all further downstream integration into desirable (pre-)products. Independent of their position along the value chain, typical industrial stakeholder directly face exactly two of those gaps. They all hope to create an offer of technologically enhanced products relevant to their downstream customers and, thus, may require technologically enhanced supplies themselves.

The ability to deliver enhanced value to end customers will determine the fate of any conceivable value chain. Eventually, these may create GRM impact on economic and societal levels that may be decisive for the future appreciation of the underlying scientific research. We designed and implemented the 3I concept following the value chain approach (figure 3) to gain in-depth insights into the status of GRM-enabled innovations and the prospects for their diffusion. Our 3I analyses always focus on very specific applications of GRM and their potential utilization in certain downstream industries. Thus, individual results exclusively highlight the selected innovation chain. Combined, the continuously growing ensemble of our focus studies approximate the overall status and prospects of GRM-enabled innovation.

1.3. Graphene Road Briefs

Our novel format of Graphene Roadmap Briefs intends to close a crucial gap in the literature with a specific focus on innovation enabled by GRM. Peer-reviewed publications and patent records usually document progress in science and technology dimensions pretty well. Review articles regularly summarize the progress for popular aspects and applications of GRM. Scientific roadmap articles usually complement broader progress reports with aggregated visions of leading researchers. In contrast, market dimensions lack a systematic literature base. Company reporting often specifically avoids the disclosure of key information, while incentives may exist to emphasize side aspects of lesser relevancy. Market studies typically attempt to aggregate, quantify, and project market intelligence. However, no external quality assurance mechanisms comparable to peer-review or patent examination exist and the merit of market projections may only become visible in hindsight.

Graphene Roadmap Briefs neither attempt to compete with scientific roadmaps nor with market studies. In contrast, our innovation roadmaps explore the largely uncharted territory in between these categories. They aggregate in-depths insights into the emerging GRM IS. We focus to resolve qualitative interrelations that may determine the diffusion of GRM and their applications, including the economic context and non-technological frame conditions. In this sense, innovation roadmaps complement scientific ones, but the different nature of their content requires separate modes of publication.

Scientific roadmaps often take years of meticulous refining from the initial aggregation of visions to their eventual publication (exemplified by figure 1 above). The authors may still add in novel results appearing in the scientific literature in the meantime, which may rather enhance the quality of results. In contrast, innovation roadmaps aggregate the insights and expectations of the involved industry experts at the very time of analysis. Their judgment, markets, and economic boundary conditions may all be subject sudden changes opposed to the rather steady growth of the S&T knowledge base. Hence, older innovation roadmaps still provide intriguing insights into innovation status and prospects at the time of analysis, but they may lose some of their immediate relevance over time.

Over the past years, the Graphene Flagship increasingly focuses the industrialization of GRM. The TIR process aggregates a common view to guide GRM research towards market demands. In this context, it addresses three major target groups: (a) the internal Graphene Flagship community; (b) external research communities; and (c) industry (promoting the recognition of future GRM application potentials). The objective of the TIR process gradually shifts from a focus on informing internal planning towards the inclusion of external actors. Here, the new format of Graphene Roadmap Briefs shall enable timely publication of key TIR results to enhance their accessibility beyond Graphene Flagship members and external experts that contribute to our analyses.

We dedicate this inaugural issue to provide context to our present TIR work in historic, conceptual and methodical dimensions, concluding with a coarse overview of the broad GRM application portfolio and the rationale for our selection of focus topics. Future issues will detail our roadmap results for individual innovation chains or cover overarching aspects of the GRM IS derived from both explicit 3I analysis and complementary innovation research.

2. Innovation interface investigations (3I)

The objective to analyze GRM-enabled innovation in further depth quickly led us to refine our fusion approach (figure 2) towards resolution of potential future value chains (figure 3), but suitable innovation research concepts and methods for their analysis did not readily exist.

A unique combination of interrelated challenges characterizes the GRM innovation context:

- Extent: GRM promise an enormous range of application that may (or may not) influence virtually any area of technology or economic sector in some way.
- Peculiarity: however, these ways may differ fundamentally. Let alone graphene[1] [13] itself effectively coming in various forms and shapes, where suitability highly depends on application context. Hence, even universal quality scales may hard to come by.
- Emergence: as an economic factor, GRM still remain in their infancy. Crucial elements such as supply infrastructure, an industrial knowledge base, or business networks hardly exist or just begin to develop.

We developed the 3I concept to overcome these challenges and to derive in-depth insights into GRM-enable innovation. We begin with a brief discussion of innovation research concepts before we introduce key 3I concepts in similar brevity here. In essence, the versatile 3I concept represents the underlying framework for our recent and future TIR work. Future issues of Graphene Roadmap Briefs will focus on the obtained results, while we plan an elaborate discussion of the 3I framework and its impact on innovation research in an appropriate venue once a few practical results are publicly available.

2.1. Innovation research context

Our TIR research is embedded in the theoretical framework of ISs [14] that initially intended to develop an understanding of innovation capacities on regional or national levels. However, TISs [15] often straddle both geographical and sectoral boundaries. Due to the fundamental nature of materials innovation, GRM may also straddle multiple traditional TIS boundaries, but diffusion processes and, thus, visibility of their impacts may require several decades [4]. Historically, we may recognize similar, overarching MISs triggered by the emergence of novel materials and material processing capabilities (such as steel, silicon, plastics). In case GRM only become remotely as influential in the future, our earlier application portfolio analyses (figure 8) may just scratch the surface.

The actual extent of the GRM IS will probably remain debatable for years to come. Attempts to study the entirety of such a (potentially) comprehensive MIS in earliest stages of its infancy may be bound to rather abstract and macroscopic levels. In contrast, the objective of the TIR process is to explore (and potentially promote) the dynamics of GRM innovation today. On an MLP [16], we can also resolve meso- and microscopic dimensions of our scope. Macroscopically, the niche of GRM may eventually enter the rather abstract regime of the general materials. In practice, such a long-term process will consist of numerous semi-independent interactions at the level of specific GRM applications or even end-product categories.

For instance, GRM represent niche conductivity additives for battery electrodes and promise to complement this regime covered by carbon black today. Similar niche-regime relations exist on the level of novel battery concepts to challenge current lithium-ion technology, or electric mobility versus internal combustion engine vehicles. In principle, each level (almost) constitutes a TIS in its own right. However, (sub-)TIS interactions determine the dynamic of the overarching innovation process. In retrospect, crucial MIS (such as steel, silicon, plastics) inflict major

[1] Not in its fundamental definition as a single perfect monolayer, but in available or conceivable forms of materials supply commonly associated with the term graphene.

impact on our entire society and most of its subsystems. In early anticipation, novel MIS often drive major hype cycles. Eventually, induced value creation for future end-customers will determine their actual relevance.

2.2. Conceptual framework

Fundamentally, we may argue that the discovery of GRM triggered the emergence a new MIS, which currently remains in earliest stages of its infancy. Hence, that MIS merely exists as a meta-level construct and consists of (perhaps rather overlaps with) a growing number of semi-independent (and usually pre-existing) TIS. In particular, the primary material innovation (GRM) gains its entire impact by enabling secondary and tertiary innovations in subsequent TIS.

Here, the rationale to consider innovation 'both an individual and a collective act' [17] therefore gains particular relevance. Virtually any conceivable GRM-enabled innovation requires the emergence or transformation of complex, cross-sectoral value networks. However, the judgment of individual actors (entrepreneurs, innovators) relevant for the emerging MIS mainly applies to their own position in present or any future value chains (which represent specific strains of the comprehensive MIS).

In incumbent TIS, vertical knowledge exchange mechanisms develop along established supply–demand relationships, often manifested in bilateral co-development projects protected by strict non-disclosure. Value chain oriented research and development as sketched in figure 3 constitutes common practice in mature industries. In contrast, novel niche technologies often not only lack critical mass and momentum, but also established interfaces with potential value chain partners on up- and downstream level. We consider this imbalance amongst the key driving factors for 'all kinds of evolutionary improvements' at regime level often to outcompete alternatives at niche level, and therefore stabilize the empirical observation that 'technological progress often proceeds along certain trajectories' [18].

2.3. The innovation chain logic

The objective of our TIR work, however, is to analyze and, possibly, promote the innovation dynamics enabled by GRM. The emergent status of that MIS obviously implies that conceivable future value chains only achieve unfavorable niche status at best today. Often they plainly do not quite exist yet. Of course, many GRM applications may not outperform conventional or alternative solutions and, thus, eventually fail for technical reasons. In other cases, however, the inertia of the conventional technology regime may suppress or at least delay the diffusion of favorable solutions enabled by GRM.

Hence, we translate our objective into the identification and evaluation of promising potential future value chains. Ideally, our activities may even stimulate crucial exchange processes, and thus contribute to the mitigation of inherent niche disadvantages. The success of our approach bases on a bottom-up approach, where we construct and iteratively refine purpose oriented innovation chains as hypothetical analogues to actual value chains. Following our refined approach in figure 3, innovation chains consist of innovation spheres that replicate major supply chain levels. Finally, we identify the hypothetical market levels that foreshadow future supply–demand relationships between neighboring innovation spheres as innovation interfaces.

2.3.1. Innovation spheres

By definition, any innovation chain itself is yet to emerge. However, many potential actors (in terms of both the economic entities and individual experts) already exist today. We assign individual actors to innovation spheres based on common bodies of shared relevant knowledge resembling their position along the anticipated supply chain. Often, individual innovation spheres overlap well with specific TIS that already exist today[2]. Hence, horizontal interactions between actors from any given innovation sphere often already occur rather frequently today (at conferences or trade shows, in industry associations or joint research projects, etc).

Note that an innovation sphere will not assemble arbitrary members of the relevant TIS, but that (often tiny) subset most likely to intersect with the emergent GRM-based MIS. We always tailor innovation spheres to their sole purpose to form the most meaningful building block of the innovation chain in question. They may span several sub-spheres, in particular if several value creation steps co-exist within typical industrial entities or otherwise feature relatively high proximity to each other. Both extent and volume of innovation spheres may vary significantly depending on maturity, vertical integration status, market size, and similar characteristics associated to the underlying TIS. Finally, innovation sphere delineation always remains dynamic in the context of their utilization. Spheres from different innovation chains may overlap, split or merge to serve their purpose best.

2.3.2. Innovation interfaces

While precursors of innovation spheres usually already exist today, major elements of the innovation chain remain hypothetical. In particular, vertical exchange (between neighboring innovation spheres) usually only occurs on a purely coincidental basis (if at all). Relevant knowledge may exist, but remain scattered or isolated. Its distribution often depends on personal interests and distinguished individuals.

[2] TIS definition may be fluid as well but sectoral delineation often applies. Here, we rather relate to narrower subsets associated to a major step within the value creation process.

We refer to all conceivable interactions between different innovation spheres as their innovation interface. Its formation likely reduces the gap between the supply and demand of novel technology. Thus, it paves the way for market formation and the diffusion of the underlying innovation, i.e. a specific GRM application and its downstream utilization driven by concrete customer benefits.

Note that innovation interfaces replicate the function of established demand-supply relationships in mature value chains. The latter may also form catalysts of innovation or vectors of their diffusion. Value chain partners often engage in bilateral research and development initiatives that usually target incremental innovations. The gain of competitive advantages within extensive added-value networks usually motivates such partnerships. Hence, protection by strict non-disclosure terms constitute common practice.

As we modeled the innovation chain logic after existing value chains, we can easily translate our terminology. We recognize highly formalized innovation interfaces opaque to outsiders in mature value networks opposed to purely coincidental ones in emerging innovation chains. The typical superiority of regime technology over alternative niche solutions bases on incremental innovation multiplied by strength in numbers, as present economic success strongly populates the involved innovation spheres.

2.3.3. Potential impact of 3I focus analysis

In line with our goals and scope described above, we utilize the innovation chain logic to study the emergence of the novel MIS triggered by GRM in an early stage of its infancy. We may only speculate about its future impact in its entirety[3], but our 3I framework enables us to analyze specific innovation chains as exemplary strains of this MIS in the making. Here, we attempt to turn the inherent niche disadvantage (established vs. barely existent) in our favor.

Strong incentives (of gaining or maintaining competitive advantages) effectively enforce the opacity of established innovation interfaces. In contrast, we are able to target a much earlier innovation stage well before protection of core intellectual property strongly inhibits open discussions among stakeholders. Just considering the extent and effort of the existing innovation and qualification cycles of the individual industries involved, large-volume application of the aspired GRM innovations typically lies at least 5–10 years ahead, often even further beyond. In particular, the final GRM utilizations further downstream range on very low TRLs. Hence, these topics largely remain subject to hype cycles, to scientific research and public funding initiatives, and to curiosity and skepticism within the indirectly involved innovation spheres. In other words, it is not too much at stake quite yet for crucial innovation agents (and prospective stakeholders of the future supply chain), thus they usually face far less restrictions and may openly engage in discussions.

At this early innovation stage, our 3I focus analyses not only explore, but also foster emerging innovation interfaces. They explicitly intend to stimulate open and critical exchange among key experts covering crucial perspectives all along the envisioned innovation chain. Our team both gathers and distributes relevant knowledge beyond usual peer groups. Ideally, our results replace vague speculations with balanced consensus expectations and, thus, contribute to the mitigation of inherent niche disadvantages.

3. Implementation process for 3I focus analysis

In practice, 3I focus analyses consist of a sequence of four consecutive stages of investigation that follow the identification and selection of a certain GRM application area for in-depth exploration. Designated members of the Graphene Roadmap Team first draft and refine a relevant innovation chain of interest, before engaging in an intense stakeholder consultation process. It eventually concludes in a highly interactive 3I focus workshop, where key experts develop an explorative innovation roadmap for all relevant innovation spheres and interfaces with us. Finally, we systematically aggregate all accumulated results in a roadmap report validated by workshop participants and an extended expert pool. The success of 3I focus analyses critically depends on expertise of the involved staff in both methods and content as well as on integral support by complementary innovation research techniques.

3.1. Conception phase

Our focus investigations tie in with earlier TIR results, which resolved desired GRM utilization benefits over the full breadth of conceivable applications. In contrast, we now specifically focus a single field of envisioned technology for in-depth resolution of the associated innovation framework. It includes understanding the full value creation process down to final product level, current solutions in the market and their expected development trajectories, and other conceivable contenders. Beyond desk research, we often attend scientific conferences and trade fairs and involve a key actor as an advisor early on in a specific 3I campaign.

[3] While many visions for GRM technology may never materialize, long-term implications may still reside beyond our comprehension. In case GRM become as impactful some day as the silicon MIS is today, our perspective on it may still be as imprecise as a 1960s vision of present-day information technology. Note that the latter represents a rather direct consequence of the emergence of silicon technology from the 1960s onwards, but also includes its previously unforeseen impacts on various TIS (including both pre-existing and newly formed ones).

The identification of the most relevant final product market(s)[4] for the specific GRM application (area) selected for investigation allows us to trace the envisioned supply chain back to GRM supply and production as a (potentially) relevant value creation process. It usually entails several value-added steps from the supply of relevant GRM, specific GRM applications, relevant integration steps into components or systems to the manufacture of final products promising competitive advantages over the present state-of-the-art.

The result of the conception stage constitutes a draft design for the most relevant stakeholder groups that will function as innovation spheres in the following stages. Simultaneously, the researchers achieve a certain level of technical literacy all along the considered innovation chain that serves as an essential requisite for all further steps.

3.2. Consultation phase

For the further elaboration of the innovation chain, we then engage in an extensive expert consultation strategy. Here, our role is comparable to an honest broker of information, who experts trust to share both personal opinions and confidential information with. In general (and often explicitly), we ensure our consultation partners of a high level of confidentiality inspired by Chatham House Rule [19]. We also approach them at a qualified eye level[5] and often specifically request their insights and opinions to controversial topics in the field. Due to the highly specialized (and often speculative) nature of the topic, the base of relevant experts usually is extremely small. Every individual may bring a very different perspective and knowledge base due to their different position in the innovation chain. Literature, patents and market studies[6], identify initial key stakeholders, while we iteratively extend our expert pool based on recommendations. Eventually, increasing frequency of reference to identical experts from different angles indicates a comprehensive mapping of the innovation chain under investigation.

Goals of the consultation process include the consolidation and validation of the insights gained regarding the respective application area, testing and refining the layout of the innovation spheres, critical discussion of the prospects and shortfalls of the envisioned technology, and distribution of information regarding the ongoing 3I initiative. In particular, consultations also serve as a pre-selection mechanism to identify and select particularly distinguished experts capable to represent key perspectives all along the entire innovation chain at the roadmap workshop our 3I study culminates in. The results of the consultation phase include a provisional summary of content results that we share with confirmed participants to support their preparation for the workshop and to provide us with an initial validation of our findings.

3.3. Interactive 3I roadmap workshop

The 3I workshop concept significantly differs from typical formats in natural sciences or engineering (that often simply accumulate PowerPoint presentations) and provides an active, participative setting based on moderated group discussions. The concept relies (a) on the complementary expertise of the participants basically representing all major aspects of the envisioned value chain, (b) on an open discussion atmosphere ensured by adequate confidentiality agreements (in analogy to Chatham House Rule [19]), and (c) on adequate group size. The careful selection of participants (based on personal evaluation from the consultation process) hence represents a critical requisite for a successful workshop. Explicit goals of the workshop include (a) identification of the present status and anticipated developments of the individual key industries along the innovation chain, (b) definition and critical discussion of common KPIs across the innovation chain, and (c) technologic, economic, and temporal alignment of the development perspectives in the frame of a specific innovation roadmap. Implicit goals include the exchange of information and perspectives along the envisioned innovation chain (including networking opportunities) to uncover collaboration potentials and, eventually, market advantages for the participating entities and the European economy in general.

Typically, a 3I focus workshop assembles a carefully balanced selection of about 20 key experts[7] whose collective perspectives cover the entire innovation chain. However, most individual perspectives usually represent core aspects of a single innovation sphere. Sometimes individuals already straddle one of the innovation interfaces we identified, or represent overarching aspects (such as regulation, standardization, public funding, private equity, policy, etc). Three major steps of interactive discussions structure the workshop agenda towards an

[4] Relevancy criteria typically include both external (European industrial base, global market position and structure) and internal (exemplary character representing common market challenges, complementary character within in our growing ensemble of focus investigations) factors.

[5] Of course, we can never achieve the level of expertise and experience of experts within the specific innovation sphere they are active in. Our specific knowledge lies in the innovation chain. As the innovation interfaces usually are pre-mature at best, we often can provide relevant insights into the situation of prior and subsequent innovation spheres. Thus, we usually lead discussions of mutual interest and bilateral exchange of information, in stark contrast to common interview settings.

[6] Search strategies include both content-driven in-depth exploration and systematic in-breadth evaluation of source libraries following the principles described further below.

[7] Invitees usually include several high-level industry executives from all over Europe. Hence, we conduct all 3I focus workshops at an easy-access location (directly on Frankfurt Airport) and strictly adhered to a single-day format to facilitate their participation.

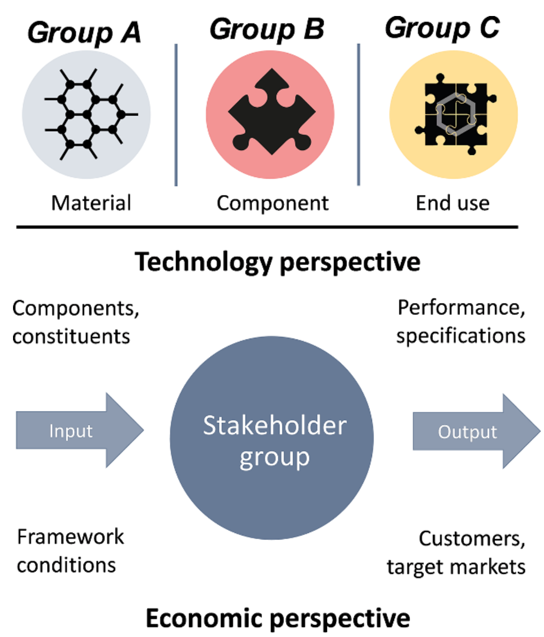

Figure 4. Schematic overview of an innovation sphere as stakeholder group in its broader economic context (bottom) and expert group assignment (top) exemplified by a generalized innovation chain.

explorative roadmap for the innovation chain under investigation.

3.3.1. Input/output analysis at innovation sphere level
An initial round of parallel discussions separately addresses each innovation sphere involved with a focus on the present state of the respective industry. The format explicitly considers I/O factors relevant to the group as detailed in figure 4. For this purpose, the workshop forum splits into three groups with participants assigned based on their expertise and perspective. Obviously, it is essential to achieve a balanced distribution of participants throughout the entire innovation chain by careful selection of invitees beforehand.

In practice, the assignment of individuals to groups can be implemented either by free choice of participants or via pre-assignment by the facilitators (e.g. by subtle markers on name badges) based on prior impressions from the consultation process. Our 3I principles ensure a stringent design of the innovation chain and according invitation of experts. Hence, group composition should essentially not depend on the assignment process, and we gained equally good experience with both approaches. Ideally, self-assignment may enhance the identification of experts with their group. Participants, however, often appreciate clear directions when exposed to the still unfamiliar 3I format. In any case, pre-assigning experts may slightly streamline the workshop agenda, which benefits to maximize workshop results within a strictly limited timeframe.

Figure 4 lays out the input/output discussion format. The members of each stakeholder group share a common perspective based on their position in the envisioned supply chain (top). We assign each group with the task to discuss their present status and expectations for the near-term future based on I/O considerations. The format creates a common understanding of corporate entities representing the stakeholder group in the context of readily existing and/or possible future value chains. On a technical perspective (top), such entities create value turning physical pre-products and other production factors (left) into desirable products (right). In this regard, the discussion traces present and intended market interactions of the stakeholder group with both upstream suppliers and downstream clients and customers. On an economic perspective (bottom), the discussion also considers the framework conditions entities operate (left) in and the customer groups and markets they target (right). Here, relevant factors may vary significantly, from regulatory conditions, over access to capital markets, product images and perceptions in the media, etc.

We always assign at least one member of our team for active moderation to each discussion group. Moderators usually gained substantial subject-specific knowledge and personal interaction experience with the involved experts during the consultation phase, enabling them to steer the discussion in an effective fashion. We encourage participants to document central aspects of the discussion (on sticky notes) and arrange these in the I/O framework (on a board structured similar to figure 4). During the discussion, each group assigns a speaker (or a team) among them for a brief presentation of the I/O results regarding their respective innovation sphere towards the workshop plenum.

3.3.2. SWOT analysis at innovation interface level
A secondary round of parallel discussions then ties in with the earlier results in a new constellation addressing the critical innovation interfaces between the innovation spheres. The format particularly addresses the SWOT associated with joint technology and product development as detailed in figure 5. For this purpose, the workshop forum splits into two new groups. Essentially, we achieve this constellation by merging adjacent innovation spheres. Of course, this requires a split of innovation spheres in middle positions[8], either solvable by self-assignment or pre-determination.

[8] Note that our generalized layout as well as the present workshop implementation usually requires exactly three innovation spheres. However, actual value chains often feature a higher number of distinct supply levels, ideally modeled with an equal number of innovation chain steps. In practice, we merge these according to context as sub-structure of more comprehensive innovation spheres matching the practical demands for our 3I implementation. However, we can easily tailor modified 3I formats and processes to fit different framework conditions.

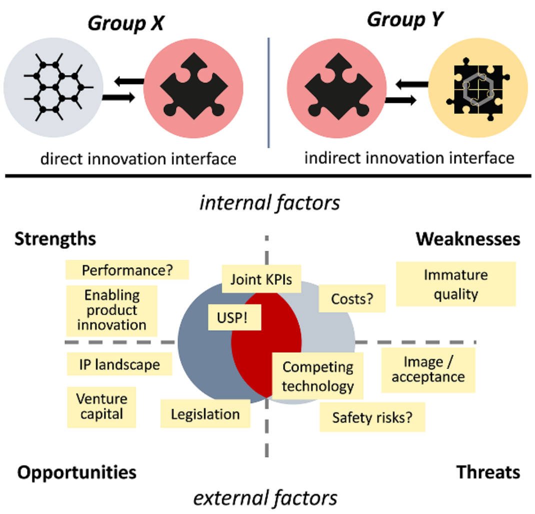

Figure 5. Schematic overview of an exemplary SWOT analysis for innovation interfaces (bottom) and suitable expert group assignment (top).

Figure 5 lays out the SWOT discussion template (bottom) for each of the considered innovation interface (top). We assign each group with the task to envision and critically discuss opportunities for collaborative technology and product development. Once the supply chain matures, the output of the upstream innovation sphere should contribute to the input of the downstream one.

Eventually, supply–demand relationships may formalize the innovation interface and govern regular interactions. At the given time, our workshop creates a unique opportunity for experts to benchmarks to their expectations and visions with those of their prospective suppliers or clients.

Typically, we ask experts to focus internal factors that the involved innovation spheres may control or at least influence first. This always includes USPs of conceivable technologies and KPIs relevant for their joint development. Topics usually also include costs, quality, performance, etc of novel technologies, products or services. Later on, moderators steer the discussion to external factors that govern the framework conditions stakeholders operate in (in case these do not automatically come up during the discussion).

Again, we request experts to document and allocate key elements of the discussion in the SWOT framework of their innovation interface (on a board structured similar to figure 5). We consider the innovation interface discussion a crucial centerpiece of our workshop. Hence, we usually dedicate two moderators to each group, reserve an essential share of the workshop time, and often allow experts to switch groups during breaks in case they want to engage on both sides. Again, the session ends with brief plenary result presentations by selected representatives of each group.

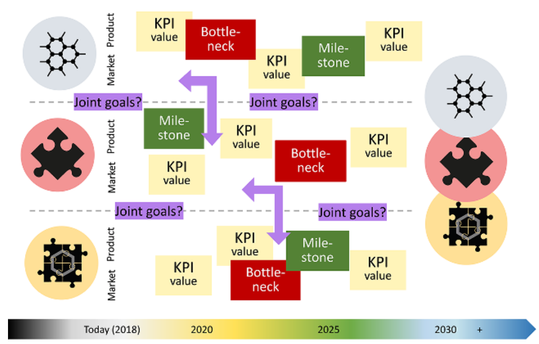

Figure 6. Schematic overview of an exploratory roadmap diagram exemplifying content specific to both innovation spheres and interfaces.

3.3.3. Exploratory roadmap at innovation chain level

In a final session, we employ explorative roadmapping techniques to allocate key results on a future timeline exemplified by figure 6. Several options exist to facilitate the transfer of key content from earlier sessions:

- Moderator led (requesting guidance from the plenum).
- Individual experts (self-organized, highly parallelized, moderators only offer support upon request).
- Group work (for each innovation sphere, moderated).
- Plenary format (directly combining result discussion).

We gained good experiences with all the approaches above including certain combinations thereof. Usually, we come prepared for various options and decide for the most promising format on the spot considering group dynamics, timing, and specifics of the topic. No matter how the results took place, we always dedicate the final portion of the workshop to a plenary discussion focusing the alignment of activities across innovation interfaces.

Figure 6 lays out our fundamental roadmap design. On the horizontal axis, we provide a timeline roughly assigning short-term, medium-term, and long-term time horizons to certain years. The vertical axis indicates the envisioned value creation process illustrated by the sequence of innovation spheres. In the aspired success scenario, stakeholders will successively build an active supply chain jointly creating competitive products. At present, most experts mostly consider timelines and target values for KPIs (yellow), milestones (green), and bottlenecks (red) for their very own innovation sphere (and usually in internally relevant metrics). Hence, we often allow for initial group work targeting individual roadmaps for each innovation spheres first (see above). The final plenary discussion then challenges the alignment of time scales (whether expected inputs become available in time, or novel output supply streams may match a market demand) and serves the identification of joint goals and common KPI across innovation interfaces (to support the formation of supply–demand relationships when the value chain emerges).

3.3.4. Documentation phase

Finally, the involved members of the Graphene Roadmap Team aggregate the essential results obtained throughout the 3I campaign in a comprehensive report. A draft is circulated amongst the workshop participant and an extended expert pool (formed by qualified expert that were not able to follow their invitation to attend the workshop) for further feedback and validation. Eventually, we distribute the final version of the roadmap focus report among the involved experts concluding the focus investigation. We periodically feed aggregated results (typically combining several roadmap focus reports, comprehensive meta-analyses, and complementary innovation research on GRM) back into the Graphene Flagship. Selective content will be further refined for publication, primarily in the form of Graphene Roadmap Briefs.

3.4. Complementary innovation research

The 3I approach clearly focusses qualitative in-depth innovation research, and we have adopted many established elements from qualitative research approaches towards utilization in 3I context. However, the success of 3I initiatives also relies on access to appropriate quantitative innovation research practices and their results. In particular, we utilize quantitative analyses regarding science, technology, and market dimensions to analyze and monitor general global trends in GRM-related research and innovation.

3.4.1. Bibliometry and patent analysis

Scientific publications reflect research activities, while patent applications refer to rather market-oriented technology development activities. For publication searches, we often utilize the online version of the database Scopus to benefit from regular updates and, thus, coverage of most recent publications. Key word searches for title, abstract, the author key words or the supplementary terms constitute common practice. Patent analyses also often utilize key word based search strategies in the PATSTAT database of the European Patent Office (EPO) and in the World Patents Index (WPI) online database. While the former covers the patent applications of about 50 patent offices worldwide, the latter provides better text disclosure due to the transformation of the official abstracts into more useful technical descriptions. Typically, we first compose the basic definition of our samples employing WPI. A transfer to PATSTAT

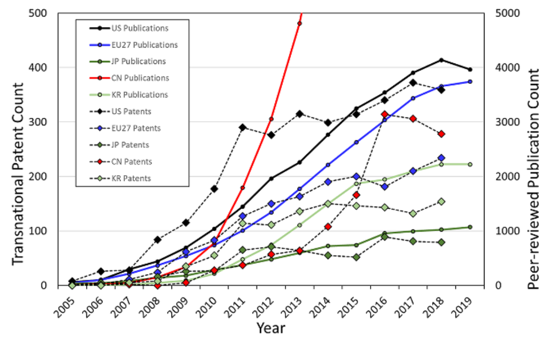

Figure 7. External innovation landscape based on publication (solid) and patent (dashed) records.

then provides access to better analysis tools. Figure 7 exemplifies results obtained for graphene. Publications usually appear at a rate of 8–10 times higher than patents in fields of knowledge-intense technologies such as graphene. At different intensities, very similar developments occurred at most global markets (e.g. US, JP, KR): patent counts developed at higher dynamic in early years and roughly turned into a saturation mode starting in 2011, while publication numbers transitioned rather steadily from exponential to linear behavior.

Note that patent searches at specific domestic patent offices inevitably lead to a domestic advantage for the analyzed country [20]. Transnational patent records avoid such bias as combining either applications at the European Patent Office or international applications according to the Patent Cooperation Treaty (PCT). In both cases the applications aim at several external markets and the cost of applications are substantial (between 20 000 and 70 000 €). Therefore, transnational patents represent a selection of applications with high economic value, and offer the possibility of a fair country comparison.

3.4.2. Meta-market analysis

Fraunhofer ISI developed mechanisms for meta-market analysis to cope with specific challenges of emerging technologies and related markets. Market forecast for mature and maturing markets usually rely on ample consolidated experience from past years enabling reasonable predictions of growth rates and, thus, forecasts for the market developments. In contrast, emerging markets face numerous (and often interdependent) sources of additional uncertainty, including:

- frequent emergence of novel players (companies),
- instable and discontinuous grows of existing players (jumping through pilot and small series production scales),
- tiny market volumes combined with extreme growth rates,
- absence of established value chains,

- high current cost levels often perceived prohibitive for many utilizations,
- high cost reduction pressure and mitigation strategies relying on economics of scale,
- lacking market uptake and acceptance on client (B2B) and consumer (B2C) levels,
- unestablished regulatory and other frame conditions, and
- hype cycle dynamics of inflated or disappointed expectations shared across most stakeholders.

Initial market studies usually appear in the emergence phase and may dramatically over- or underestimate the future development of the market. Subsequent market forecasts then often refer to the initial market assessments creating a path dependency for similar (if not identical) predictions. Simultaneously, other market analyst may apply different assumptions that result into drastically different predictions. In general, the quality of the market research (e.g. based either on rough guesses and estimates or on reliable information such as announced investments, production capacity extensions, etc) may differ between studies and involved analysts.

In the frame of meta-market analysis, we combine predictions from the various available market studies and analyze their results in the context of plausible market development scenarios. Their ensemble reveals deviations and similarities, differences in assumptions, mechanisms and, thus, market sizes, growth rates, etc. Despite challenges including inconsistent definitions (of products, regions, and markets), limited access and transparency, as well as differences in forecasting periods, our meta-market analyses also measure the level uncertainty the state of market consolidation. Please refer to [4] for a preview of our data. We implement key meta-market conclusions in all results, including our roadmap on industrialization status and prospects 2020 [13]. A forthcoming issue of Graphene Roadmap Briefs will explicitly cover meta-market methodology and results.

4. Initial GRM application portfolio assessment

Earlier TIR results formed the starting point for our focus investigation strategy for in-depth resolution of GRM innovation potentials. In particular, the in-breadth assessment of the various GRM application areas foreseen by scientists regarding their innovation prospects represented a key factor informing our selection of focus topics. Its full results form an integral part of the comprehensive 2017 TIR version [10], which is currently refined for publication (see above). Here, we only present a highly aggregated portfolio summary to illustrate its impact on subsequent TIR initiatives.

4.1. Preparation

Once receiving an initial grant to develop and implement a continuous roadmap process to advance the initial S&T roadmap [8], Fraunhofer ISI began to elaborate the initial phase of the TIR process combining various qualitative and quantitative methods in 2014. Desk research concentrated analyzing the existing S&T roadmap, complementary literature, and market studies. Application specific innovation aspects were aggregated from a series of expert interviews (face-to-face and by phone) with work package leaders of the Graphene Flagship as well as industrial representatives both within and beyond the project consortium. The semi-structured interviews covered a broad range of innovation aspects, including:

- technology: performance today, performance potential, USP, complexity, ease of use;
- production: scalability today, scalability potential, integrativeness today, integrativeness potential, production cost;
- applications: cost reduction today, cost reduction potential, diversity of applications, product value;
- market: justified cost vs. function gain, market volume, market competitiveness;
- timing: time to market assessment.

In total, we carried out 65 interviews in the initial TIR phase. Among those, 63% of the interview partners carried Graphene Flagship affiliations (members or associates), while 71% represented industrial entities (both within and beyond the project). An initial, Graphene Flagship internal workshop informed project members about the progress of the TIR strategy and gathered their feedback and recent insights on 13 October 2015 in Berlin.

4.2. Implementation

Our analysis culminated in two broad roadmap workshops assembling stakeholders from industry and research. They served (a) the validation and refinement of our results, (b) their further harmonization, and (c) creation of common views on GRM utilization prospects in major application areas. Three major sessions structured both workshops. They started with an analysis of (SWOT associated with individual GRM application areas, followed by a portfolio analysis aggregating the insights of the participants into both technical and market potential for each topic. Finally, a roadmap session explicitly aggregated estimates on contemporary TRLs, the timing and development path for GRM utilization in various application areas and related markets, as well as important challenges and barriers (red brick walls).

Table 1 provides an overview on organizational details for both roadmap workshops informing our assessment of the GRM application portfolio below. We received strongly positive feedback from participants, appreciating the forum for combining research and industry, for promoting exchange of ideas, for gaining new ideas and perspectives, as well as for successful implementation and productive outcomes. However, some industrial participants hesitated disclosing information on KPI and internal GRM-related activities for confidentiality reasons.

4.3. Outline of results

We aggregated the workshop results on semi-empirical scales from most (++) to least (−) promising on both technology and market dimensions for all GRM application areas assessed. The technology potential dimension summarizes the benefit of GRM utilization compared to existing and other conceivable solutions in the field, while market potential dimension considers the economic prospects of novel solutions particularly regarding the European market (domestic from the perspective of the Graphene Flagship). In particular, the ratings have been discussed and validated by the participants of both workshops described above.

In total, the 2017 TIR version [10] identified and covered 73 GRM application areas. Figure 8 provides a highest-level portfolio overview for all those receiving a strictly positive assessment of both technology and market perspectives then. It groups individual application areas in four major fields of application. Their definitions remain broad and may overlap, but still provide readers better access and indicate a certain level of commonality for each field.

Their coarse descriptions below can only provide a first glimpse. We highly recommend the full 2017 roadmap [10] and its refined publication version (to appear soon) for full context and reference. The exemplary citations below only point to a few highly recognized scientific review papers without indicating a particular preference for their content over numerous similar high-quality publications.

4.3.1. Composites and coatings

Enhanced functionality motivates the potential use of GRM as additive to composites [21, 22] or coating layers. GRM incorporation in composites enables a multitude of application opportunities with rather low technical requisites (platelets may often suffice), but high economic sensitivity (low price, high volume). Important topics include functionalization of GRM for achieving optimum dispersion, potential environmental and health risks, and public perception ranging from 'wonder material' to 'the next CNT' (carbon nano tubes). This also applies to the coating and paint sector at a different cost–benefit relation. GRM use as additive to liquids features even lower implementation barriers, e.g. for drilling fluids. Other application areas include functional membranes (desalination, water purification) or photocatalytic use in combination with TiO_2.

4.3.2. Energy generation and storage

In general, energy applications potentially open up distinct high-volume markets for GRM in a field of high innovation affinity [23, 24]. Novel technologies may disperse quickly if backed by a USP and by competitive cost–benefit relations. In the energy storage sector, graphene constitutes a candidate electrode additive for enhanced lithium-ion batteries, 4th generation battery concepts (including lithium–sulphur, lithium–air, redox-flow), as well as supercapacitors. So far, Asian players dominate the growing energy storage market. Novel end-product segments require advanced performance and decreasing costs, which enables some opportunities for GRM incorporation. European companies show strengths in certain market niches. Supercapacitors offer higher power density and dynamic storage. GRM-enabled performance gains may pave their way towards better market penetration. In the energy conversion sector, GRM appear highly promising as electrocatalyst for fuel cells, where they may unlock significant cost reduction potential in case replacing noble metals such as platinum. However, the technical progress with fuel cell vehicles may suffer from public and political preference currently given to battery electric vehicles. In renewable energy generation, GRM hold significant promise in the photovoltaic sector as potential replacement of transparent conductive oxide top contacts, but more mature technologies such as silver nano-wires constitute tough competition. Innovative perovskite solar cell technologies may compete with or complement the dominant material standard (silicon) and GRM may serve as an enabler for charge collection.

4.3.3. Electronics and photonics

Diverse GRM applications may occur in telecommunication, optoelectronics, photonics, computing, sensors, flexible and printed electronics [25, 26]. Most require highest material quality such as single-layer graphene with low or no tolerance for defects. Wafer-scale integration is a significant challenge and induces high time to market. Cross cutting issues address front-end-of-line and back-end-of-line as well as packaging in semiconductor fabrication. GRM hold promise in optoelectronics for high-speed communication, mobile telecommunication (5G and beyond) appears particularly relevant for the European economy. The absence of a bandgap disqualifies graphene for classical computing applications, but functionalization and other 2D materials appear promising for logic circuits in the context of further progressing miniaturization. Global trends such as Internet of Things, Industry 4.0, mobile electronics, or autonomous driving create a mass market for various integrated sensors, where granular niche markets enable diverse opportunities for early market entry of innovative GRM-based solutions.

Table 1. Graphene Roadmap workshops (2016).

	Workshop 1	Workshop 2	Total
Date	19 January 2016	5 February 2016	
Location	Squaire Conference Centre, Frankfurt Airport, Germany		
Number of participants	47	35	82
Participants from industry	26	20	46

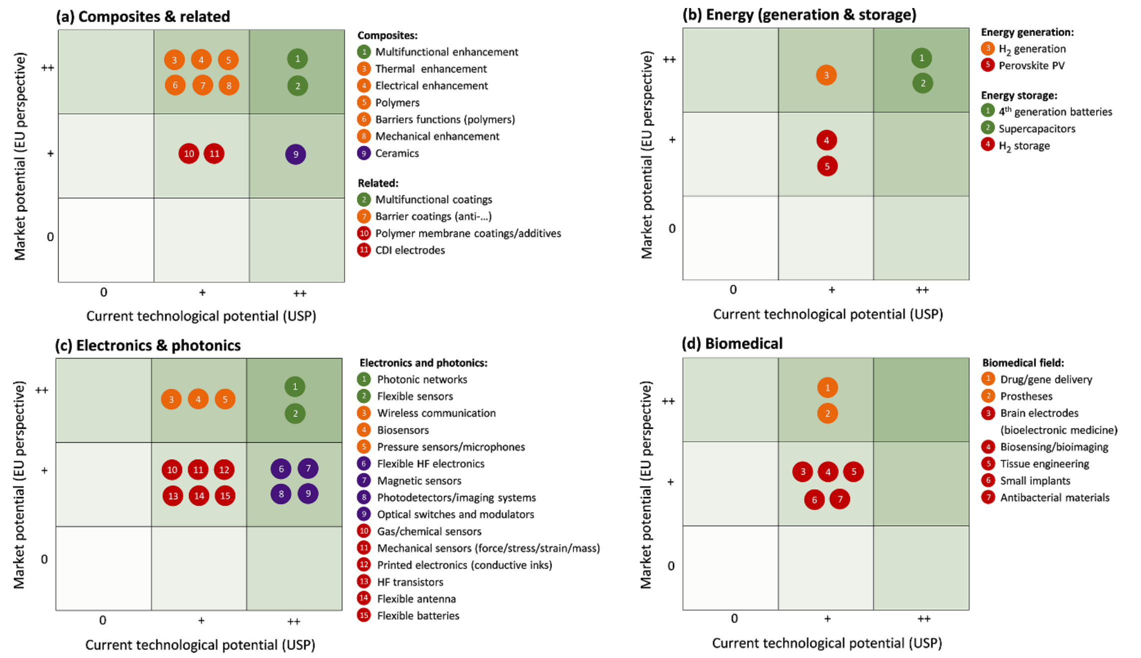

Figure 8. Portfolio overview of the most promising graphene applications according to TIR results.

The juvenile market of flexible and printed electronics sets low entry barriers for GRM, and first conductive inks based on graphene are already commercially available today.

4.3.4. Biomedical

The biomedical field promises unique application opportunities for GRM [27, 28]. Medical devices benefitting from GRM-based coatings, composites, or sensors may be closest to market. Unique emerging applications in the biomedical field include flexible, wearable, and mobile devices as well as drug delivery. Pharmaceutical and medical device markets feature exceptional regulation, thus require extensive proof of quality, safety and efficacy.

5. Focus topic portfolio and selection process

Beyond a coherent approach, its stringent implementation, and the competency of the Graphene Roadmap Team, the selection of most relevant topics constitutes a crucial factor for the success of our focus investigation strategy. We recognize a set of both external and internal criteria that we aspire to meet simultaneously with every single topic selected. External criteria summarize the relevance and significance of the topic of choice, including questions such as:

- Is there a USP for GRM utilization?
- Do we recognize substantial potential for market impact?
- In what extent may European industries be involved?
- In what extent is the Graphene Flagship involved?

In contrast, internal criteria summarize the perspective and requisites of the TIR process, including questions such as:

- Does the topic promise significant roadmap results?
- Will we likely be able to identify and consult with European experts that represent each step of the entire innovation chain envisioned?
- Does the topic substantially differ from and, thus, complement our ensemble of previous 3I focus studies?

In general, our approach aims to maximize the impact of both, each individual 3I issue and our growing portfolio of analyses simultaneously. Of course, 3I always deliberately focuses a tiny strain of the emerging GRM IS, but already a surprisingly small number may represent a much broader field-of-view than might be apparent at first. Clever and complementary topic selection and design enables us to inter- and extrapolate between cases and base predictions on analogies and similarities. In particular, such triangulation also allows us to derive in-depth conclusions for the entire field based on the exemplary character of certain aspects of our results.

5.1. Initial 3I phase of the TIR process

In 2017, we began with the conception of the 3I approach and possible implementation strategies dedicated to in-depth exploration of GRM innovation context. Earlier TIR results (see chapter 4) served as a major guidance criterion for the selection of most promising topics (focusing application areas ranked strictly positive for both, technical and market prospects). Further down selection relied on qualitative and quantitative feedback from the Graphene Flagship (gathered in informal discussions as well as by a brief survey), but also on research, experience and insights of members of the Graphene Roadmap Team. Some choices also considered strategic development aspects within the Graphene Flagship (business development, alignment with technical product development initiatives).

Table 2 summarizes the initial four focus investigations executed within the current TIR phase. The dedicated format required as rather small workshop format (target group size: about 20 people) and highly diversified expertise covering the entire innovation chain. Fraunhofer ISI actively pre-selected prospective participants based on desk research and a thorough consultation process (see above). Only distinct experts bringing relevant additional expertise actually qualified for participation were invited after careful selection. Besides the total number of experts consulted within each focus investigation, the table also quantifies the number of industry perspectives[9] involved.

5.2. Maturation phase of 3I within the TIR process

The positive experience and detailed results gathered with the initial 3I studies encouraged the continuation of our focus investigation strategy from 2018 onwards. Of course, our topic selection still followed similar criteria, but we refined the process and considered additional aspects. For instance, we systematically consulted with the leadership of technical work packages throughout the Graphene Flagship to consider both their insights and most recent technical developments. We also engage in informal exchange with GRM and secondary industry experts frequently. Moreover, we began to regularly consider strategic aspects both within the Flagship and for the development of our 3I focus result portfolio.

Tables 3 and 4 summarize implementation details for the six most recent 3I focus investigations roughly grouped regarding the nature of GRM utilization. Our goals and criteria regarding target group size (about 20 people), diversity of expertise (covering the entire innovation chain), and participant selection (based on expertise, perspective, and distinction evidenced by thorough consultations) remain unchanged for all 3I studies carried out so far.

Please note that the division line between microintegration is not always sharp (for instance, the biosensor topic included both, printing of flexible devices and microsensor arrays). In total, we consulted with 219 key experts in the most recent phase of the TIR process. More than half of our consultation partners (114) represented relevant industry perspectives.

5.3. Advanced 3I concepts for upcoming TIR research

In the future, the TIR will further evolve in line with the maturation of GRM research and innovation. Our goals shift further towards informing European industry on potential future GRM value chains also involving downstream stakeholders:

- OEMs aggregate complex value networks that may change or improve when advanced GRM applications enter their supply chain. We envision the TIR to provide a reliable reference point to OEMs to identify and implement GRM-derived competitive advantages.
- Intermediary suppliers (on component, device and sub-system levels) benefit from in-depth elaboration of specific value chains. The TIR process also creates unique exchange opportunities stimulating future supply and demand relationships that are crucial for GRM industrialization.
- The primary GRM sector (e.g. producers of powders or inks) requires clear targets (cost, quality, volume, etc) derived from demands of potential customers. GRM suppliers may become key beneficiaries of more normative TIR formats.

Achieving these ambitious goals requires an intensification of our focus investigation strategy that enables us to elaborate specific value chains where GRM may provide an USP using both established and advanced formats:

- Exploration of novel topics is critical both to keep track of the dynamic emergence of novel GRM application areas and to expand the in-depth

[9] Please note that the remainder typically accounts for relevant scientific perspectives from both inside and outside the Graphene Flagship. However, depending on the topical context, also government officials, venture capitalists, business developers, non-government organizations (NGO), medical doctors, etc may be involved as well.

Table 2. Overview of the initial set of four focus investigations carried out in 2017 and 2018.

Focus topic	Super-capacitors	Anti-corrosion	Li-ion batteries	Neural interfaces	Total
Direct innovation interface	Electrodes for super-capacitors	Novel anti-corrosion coatings	Electrodes for Li-ion batteries	Medical research and evaluation	
Indirect innovation interface	Forklifts, ware-house logistics	Aerospace, auto-motive, marine	Auto-motive, wear-able devices	Advanced neural therapy	
Experts consulted	42	47	43	48	180
- from industry	37	33	29	23	122
Workshop date	4 July 2017	24 October 2017	28 November 2017	25 January 2018	
Participants	19	22	21	19	81
Workshop location	THE SQUAIRE Conference Center, Frankfurt Airport, Germany				

Table 3. Overview of recent 3I focus investigations at least partially involving GRM microintegration aspects.

Focus topic	Photonics	Biosensors	MRAM	Total
Direct innovation interface	Photonic device integration	Non-invasive diagnostic biosensors	GRM micro- and process integration	
Indirect innovation interface	Telecommunication, 5G data networks	Medical devices, lifestyle applications	Microelectronic and spin-tronic devices	
Experts consulted	27	38	27	92
- from industry	16	11	17	44
Workshop date	29 November 2018	22 May 2019	30 October 2019	—
Participants	20	26	23	69
Workshop location	THE SQUAIRE Conference Center, Frankfurt Airport, Germany			

Table 4. Overview of recent 3I focus investigations involving GRM utilizations as a bulk material in some form.

Focus topic	Photovoltaics	Water treatment	Elastomers	Total
Direct innovation interface	Perovskite solar cell com-mercialization	Filtering membranes, capa-citive deionization	Elastomer composites, functional fillers	
Indirect innovation interface	Tandem PV, building integration, flexible	Desalination, waste water, purification	Tires, consumer/sport, industrial rubber prod.	
Experts consulted	54	26	47	127
- from industry	30	13	27	70
Workshop date	27 November 2018	15 May 2019	9 October 2019	
Participants	19	17	19	55
Workshop location	THE SQUAIRE Conference Center, Frankfurt Airport, Germany			

coverage to a representative ensemble of GRM applications.
- Advanced focus investigation of highlight topics (i.e. high impact GRM application areas such as batteries) will enable to review and expand these roadmaps.
- Beyond focus formats may include vision development (e.g. for future of GRM-production in Europe), demand-side driven normative roadmapping (for the emerging GRM supply industry) and context-specific (e.g. GRM utilization in space) portfolio assessment initiatives.

The novel format of Graphene Roadmap Briefs contributes to our goal to improve timely accessibility of our results to stakeholders in industry, policy, and the public. We currently conduct a survey among past focus workshop participants, our extended expert pool, and Graphene Flagship leadership in order to support our decision process on future focus topics.

6. Conclusions and outlook

The first isolation of graphene triggered the formation of the GRM IS. Even though not all of the initial expectations came to life quite yet, GRM emerges as a highly dynamic innovation area still largely driven by scientific discovery over an extremely broad spectrum of applications and utilizations. We developed a new roadmap approach in our attempt to predict future value chains enabled by GRM well before the practical supply chain establishes. Our analyses focus the ability of GRM to meet needs on industrial and societal levels and the in-depth resolution of promising pathways to achieve this overarching goal. Our novel 3I mechanism proofs versatile for adaption to the broad diversity of GRM applications embedded into widely deviating innovation contexts. Thus, it proofs instrumental not only to predict the magnitude and impact of the emerging GRM IS, but also to foster the formation of innovation interfaces crucial to the industrialization process.

We recognize a high potential to apply 3I concepts to other technology intense innovation areas and adopt the underlying mechanisms to resolve their complexity.

Over the past 3 years, we completed ten 3I studies each resolving a specific innovation chain based on GRM in depth. Each represents a single strain of the emerging GRM IS. Individually, a single 3I study always highlights just one out of endless conceivable future value chains possibly to base on or benefit from GRM utilization. However, their ensemble measures the entirety of the GRM IS at an increasing level of detail. Our topic selection targets both, individual and collective merit. Of course, each choice shall resolve compelling aspects of GRM innovation down to the level of valuable final products. Simultaneously, we also screen potential topics regarding their significance as a complement to our growing ensemble of 3I studies. Collectively, they aim to span the full diversity of GRM application and, thus, to enable triangulation between their innovation contexts. Despite all results being derived highly specific to the innovation chain under investigation, we are increasingly able to distinguish their validity for similar cases or the entire GRM IS.

We will further complement the spectrum of 3I studies with novel topics in the coming years, but also revisit select 3I topics to analyze their progress and complement our focus investigation strategy with advanced methods. This inaugural issue establishes Graphene Roadmap Briefs as our primary outlet for the timely dissemination of select innovation results generated by the continuously evolving TIR process. Future issues will primarily cover individual innovation chains resolved by 3I studies, overarching analyses, and related innovation content. Ideally, public access to common views aggregated in our roadmaps from complementary stakeholder perspectives by a neutral instance will help to inform industry about and further their confidence in GRM-based innovation.

Acknowledgments

This project has received funding from the European Union's FP7 and Horizon 2020 research and innovation programmes under Grant Agreement Nos. 604391 (GRAPHENE), 696656 (GrapheneCore1), 785219 (GrapheneCore2), and 881603 (GrapheneCore3). The authors thank all past and present members of the Fraunhofer Graphene Roadmap team, in particular Michael Meister (now at Schott AG) who led the initial portfolio analysis. Our team includes Bernd Beckert, Julia Beyersdorf, Annette Braun, Piret Fischer, Michael Friedewald, Karin Herrmann, Bärbel Hüsing, Christoph Neef, Thomas Schmaltz, Ulrich Schmoch, and Axel Thielmann. We highly appreciate the input from numerous Flagship partners, industry experts, and other relevant stakeholders who we interacted with us, who participated in our workshops, and who validated our reports since 2014. We appreciate Alison Tovey from the IoP design team for her support to improve our illustrations and roadmap designs.

ORCID iD

Henning Döscher https://orcid.org/0000-0001-9352-4644

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