



# Can graphene fuel a transformative change in energy storage technologies? A scenario analysis for the next two decades

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## ABSTRACT

In this article, we explore the transformative potential of graphene in electrochemical energy technologies over the next two decades. Using a two-round Delphi survey and 28 expert interviews, we construct three distinct evolutionary scenarios: 1) *Current state*: graphene has made notable technical advancements, but its transformative potential is limited to “nice-to-have” functionalities, 2) *Projected state*: graphene's technical progress and adoption of “nice-to-have” functions in energy storage devices will continue, suggesting a gradual evolution, 3) *Ideal state*: graphene's technical barriers are surmounted, and its transformative capacities are unleashed. Our study's findings challenge the prevailing consensus, which suggests that graphene will have a transformative impact in the near term. Instead, we highlight the complex balance between “nice-to-have” functionalities and genuine transformative capacities. Additionally, we underscore the persistent technical, strategic, and systemic challenges that could shape graphene's trajectory. Finally, we provide an in-depth, analytical assessment and practical implications for both the potential of graphene in energy storage devices and broader innovation generalization dynamics.

## 1. Introduction

In the complex context of transformative innovation policy, the diffusion of innovations emerges as a foundational element, molding our current realities and visions of the future (Schot and Steinmueller, 2018). Historically, technological innovations have experienced phases of development, testing, and refinement before they become integral to society. The annals of technological progress chronicle a recurrent theme: the intriguing and substantial delay between an innovation's inception and its widespread adoption (Grubler, 2012), and such a phenomenon stands out consistently within the energy sector (Gross et al., 2018; Smil, 2017).

In particular, the widespread diffusion of innovations in electrochemical energy storage devices (EESDs) tends to experience extended timeframes (Gross et al., 2018), despite their potential contribution to addressing challenges such as climate change, one of the most pressing challenges in humankind's history (IRENA, 2021). EESDs, which include conventional lithium-ion batteries and future-generation technologies, such as lithium-sulfur and metal-air batteries (Gardner et al., 2016), offer a consistent supply of renewable energy sources at relatively low

cost (Burd et al., 2021). They could be critical in the transition towards a more reliable renewable energy ecosystem thanks to their capability to store and dispatch energy on demand, managing the intermittent nature of sources like wind and solar (Deng et al., 2020; European Commission, 2020a; Fu et al., 2021; Mejia and Kajikawa, 2020). However, as we navigate this transformation, a looming challenge persists: for EESDs to reshape our energy landscape and meet escalating demands, the discovery and widespread diffusion of innovative materials become a necessary evolution (Gallagher et al., 2006; Huang et al., 2018, 2021; Shen et al., 2018).

Graphene, a two-dimensional material composed of carbon, possesses promising characteristics for EESDs, including high electrical conductivity, extensive surface area, and superior mechanical robustness (Olabi et al., 2021; Raccichini et al., 2015). Despite widespread optimism surrounding the potential of graphene in EESDs (Bai et al., 2020; Chen et al., 2020; Liu et al., 2020), the journey to its widespread diffusion remains complex and could span many years (Döscher et al., 2021; Döscher and Reiss, 2021). Graphene's unique attributes, while often glorified for their transformative potential, also introduce a cascade of multifaceted challenges.

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For example, the synthesis and scalability of high-quality graphene remain difficult, with existing methodologies often yielding inconsistencies in material properties (Bøggild, 2018; Kauling et al., 2018; Raccichini et al., 2015). Beyond the realm of material science, the introduction of graphene fundamentally alters the architecture and design paradigms of contemporary battery systems. Its diffusion demands a re-evaluation of electrode compositions, electrolyte chemistries, and even battery management systems to ensure optimized performance and safety.

Furthermore, widespread diffusion of graphene is not merely a technical endeavor but requires a reconfiguration of various supply chain dimensions (Braun and Skinner, 2007; Huang et al., 2018, 2021; Sholl and Lively, 2016; Walton and Sholl, 2017). It demands a reassessment of supply chains, with potentially novel raw material requirements and altered manufacturing protocols. Additionally, from an economic standpoint, while graphene promises enhanced battery performance, its diffusion may entail increased upfront costs. In sum, the widespread diffusion of graphene is emblematic of the tricky interaction between technical, economic, and infrastructural adjustments, each demanding careful maneuvering to ensure the effective deployment.

Historical precedents indicate that achieving widespread diffusion in the energy sector is challenging and often demands extended timelines (Gross et al., 2018; Smil, 2017). Key factors that influence the diffusion timeframe include technology itself, the demand for the technology, and the policy and investment environment surrounding the technology. For example, lithium-ion battery cathodes, conceptualized in 1980 (Mizushima et al., 1980) only found applications in electric vehicles in 2008 – almost three decades later (Rajashékara, 2013). More broadly, Rao and Kishore (2010) assert that a mere quarter of renewable energy innovations achieve widespread diffusion. Yet, today's persistent societal challenges, underscore the urgent need for effective solutions. Waiting too long to achieve widespread diffusion would leave us unprepared to address looming threats (Huang et al., 2018).

Reflecting upon past advancements offers valuable insights. We expand the arsenal of case studies by analyzing the future trajectory of graphene's diffusion in EESDs. Situated at the juncture of ground-breaking innovation and tangible application, graphene has embarked on a journey fraught with multidimensional challenges. Yet, even as we approach a two-decade mark since its discovery, the bold transformation it once promised for EESDs remains largely unrealized (Bøggild, 2023), and may still require years to unfold.

The main aim of this study is to construct scenarios for how the diffusion of graphene in the next two decades might lead to transformative change in EESDs. In addition, we also aim to critically assess the divergence between current prioritizations and ideal prioritizations of the key determinants influencing the pursuit of transformative change and explore the implications of these discrepancies on the future evolution of graphene in EESDs. Our methodological approach builds on a two-round Delphi survey, augmented by the insights gathered from 28 personal interviews. This allows us to distinguish empirically grounded prospects of graphene's generalization in EESDs from speculative noise, offering more clarity on its potential to drive transformation. The constructed scenarios serve as strategic beacons for stakeholders spanning both the private and public actors. Moreover, our research exemplifies the potency of foresight methods, including the Delphi technique and scenario building, in uncovering the tricky dynamics that characterize the generalization of innovations.

## 2. Conceptual framework

Innovation's potential as a societal catalyst is profound, paving the way for solutions that promise transformative change (Mazzucato, 2018; Westley et al., 2011). Although transformative change is a central pillar in the third frame of innovation policy (Schot and Steinmueller, 2018), it is also emphasized in the most recent fourth frame of innovation policy (Edler et al., 2023). Transformative change refers to a fundamental and

systemic shift in a given system or domain (Geels, 2005; Markard et al., 2012; Schot and Steinmueller, 2018). This change is characterized by deep alterations in the underlying structures, paradigms, and values that govern the system. Unlike incremental or evolutionary changes, transformative change is radical in nature, leading to a significant reconfiguration of the system's components and their interactions. In essence, this is the type of change needed to address looming societal challenges. Yet, this power of innovation is not inherently altruistic (Biggi and Giuliani, 2021; Giuliani, 2018). Guided primarily by profit motives, innovation can inadvertently create imbalances, concentrating power, wealth, and influence in the hands of a select few (Lampinen et al., 2022; Pfothner et al., 2022). For example, monopolistic tendencies can inhibit competition, hinder the pace of further innovation, and limit access to vital technologies. Thus, the path of innovation is deeply swayed by the intentions guiding its spread.

The literature on how innovations spread has traditionally been dominated by Rogers' theory of diffusion of innovation (Rogers, 1962). This theory defines diffusion as the process through which innovation is spread through society in an S-curve pattern, starting with early adopters and gradually reaching the majority. While useful in many contexts, this model oversimplifies the diffusion process, neglecting key factors impeding the pursuit of transformative change (Lampinen et al., 2022). Furthermore, it fails to capture the complexities and the feedback loops often encountered in real-world scenarios specifically within the context of advanced and complex technologies. Consequently, Rogers' model falls short in addressing the multifaceted challenge of diffusing innovations specifically tailored to achieve transformative change (Wigboldus et al., 2016).

While the predominance of Rogers theory is evident, alternative frameworks have emerged to better understand innovation diffusion. Notably, the notion of "scaling" has garnered attention, focusing on the expansion of innovations' outcomes in terms of reach, impact, or adoption, moving beyond initial contexts to broader ecosystems or markets (Westley et al., 2014; Wigboldus et al., 2016). Critics argue that the rapid scaling of innovations, can be driven more by self-interest and profit motives than by genuine concern for societal advancement and broader transformative change (Lampinen et al., 2022; Pfothner et al., 2022).

Beyond scaling, we anchor our analytical approach to the notion of "generalization of innovation," following the framework developed by Wigboldus et al. (2016). We conceptualize the notion of generalization of innovation as a praxis, as depicted by the bidirectional arrow in Fig. 1, signifying its twofold nature: both an evolutionary process and an outcome to address societal challenges. This praxis rests on three foundational pillars, symbolized by three colored circles in Fig. 1. The first pillar, the principle of inclusivity and reach, underscores the imperative for innovations to resonate with and benefit a diverse array of stakeholders, transcending socioeconomic, cultural, or geographical limits (Schiller-Merkens, 2020; Tarrow, 2010). The second pillar concerns the innovation's symbiotic relationship with existing systems. For an innovation to be generalized, it must not only align with but also possess the capacity to reshape existing institutional, cultural, and socioeconomic arrangements, thereby becoming an indelible component of the system and instigating profound changes. The third pillar, depth of impact, emphasizes the profound influence an innovation exerts, not just in its breadth but in its ability to deeply transform societal sectors, from technological artifacts to community dynamics and broader policy frameworks (Cozzens and Sutz, 2014). Beyond the expansive reach emphasized in the first pillar, the depth underscores the innovation's profound cascading effects across societal levels.

This praxis intrinsically demands time for transformative change to be fully realized, suggesting that generalization needs to be construed as an evolving phenomenon. Time is a critical determinant in the journey of an innovation from its inception (i.e., the process side of the arrow in Fig. 1) to its widespread deployment and subsequent societal impact (i.e., the spread of the outcomes side) (Gross et al., 2018; Sovacool, 2016).

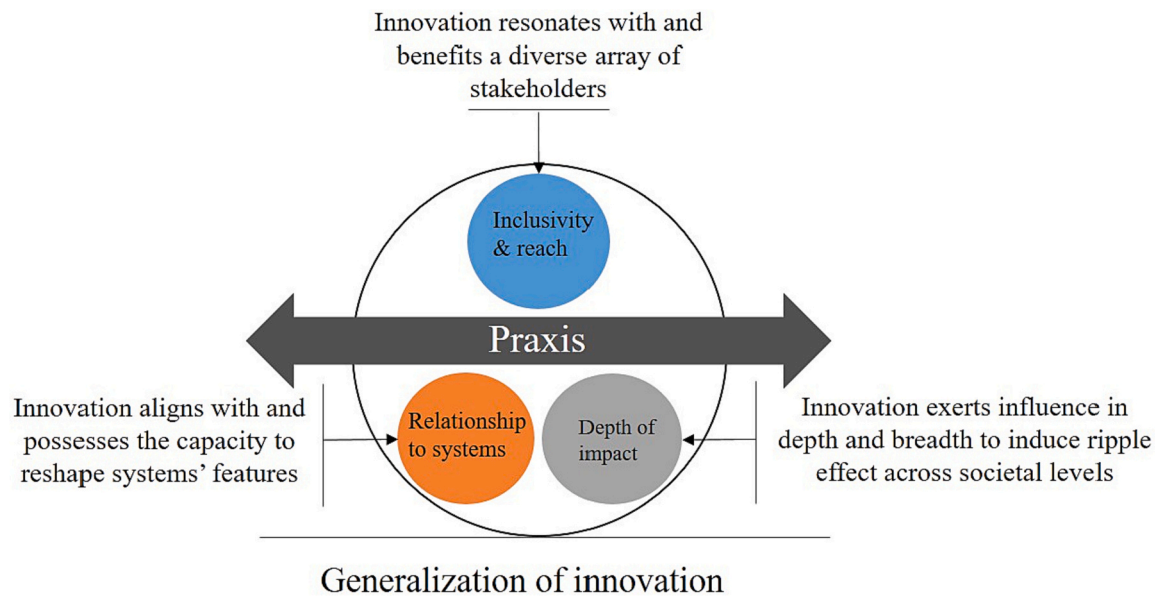


Fig. 1. Conceptualizing the generalization of innovation – source: authors' conceptual synthesis.

Digging into the history of complex technologies, particularly within the energy sector, one encounters the tale of carbon nanotubes (Baughman et al., 2002). Initially considered as a revolutionary breakthrough with the potential to redefine the energy storage (Dresselhaus et al., 2001), their anticipated transformative impact remains unrealized, despite still being a promising technology. Furthermore, the trajectory of an innovation's generalization is often muddled by the myriad actors involved (Köhler et al., 2019). When these actors operate in an uncoordinated manner, driven by disparate goals and visions, the path to generalization becomes not a singular, defined route but a sprawling web of possibilities. This discord can cause the generalization praxis to manifest in many, often capricious trajectories, thereby undermining the realization of transformative change (Larrue, 2021). In such a scenario, innovation, instead of being a beacon of progress, risks becoming a testament to missed opportunities and unfulfilled potential.

Building upon the theoretical foundations previously discussed, our empirical study aims to connect the conceptual understanding of the notion of generalization of innovation with its concrete applications in real-world contexts, illustrating the tangible challenges and opportunities intrinsic to the generalization praxis. In the subsequent subsection, we identify crucial determinants demanding targeted intervention for the generalization of graphene in EESDs. Following this identification, we label the determinants as **P1** (projection 1), **P2**, **P3**, and so forth, to streamline their presentation in the projection development section and the empirical results section. At the same time, as we postulate that the current aspirations and activities of various actors might not synchronize with the enduring objectives essential for the generalization of graphene, we also explore how these projections are prioritized compared to how they should be prioritized. Therefore, we added extra labels to facilitate their presentation in the results section. Current priority levels for projection one, for instance, are labeled as **CPP1**, and for required priority levels for projection one as **RPP1**, and so forth.

### 2.1. Graphene in EESDs: navigating progress towards the generalization praxis

In strict sense, graphene refers to a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice (Novoselov et al., 2004). However, “graphene” in commercial parlance encircles a family of graphene-related materials (Döscher et al., 2021). The spectrum of materials ranges from pristine monolayer graphene, which is seldom

available and typically reserved for lab-scale experimental endeavors, to more accessible forms like graphene oxide, reduced graphene oxide, and an array of other graphene derivatives, each varying in thickness, quality, and price. Regarding its potential, some argue that graphene is overhyped and may not be a viable solution (Alvial-Palavicino and Konrad, 2019; Konrad and Alvial-Palavicino, 2017), and practical applications remain rare (Bøggild, 2023). Others insist that it has great potential to achieve a transformative change in EESDs (Gumfekar, 2018; Olabi et al., 2021) and it is on the right pathway to delivering on its promises (Reiss et al., 2019). Yet, it remains an inescapable fact that, despite nearly two decades of research and high expectations, the tangible outcomes of graphene are still uncommon.

In particular, to realize graphene's transformative potential in EESDs, significant progress is required across multiple dimensions. However, progress in these dimensions depends on actors' decisions and their interest in achieving transformative change. The choices made by key actors such as graphene and EESDs producers will significantly influence how this progress unfolds over the next two decades (Larrue, 2021). Understanding how these actors prioritize advancement in each dimension is crucial for aligning short-term actions with long-term visions (Haidar et al., 2022). For instance, if the focus is predominantly on immediate economic gains, the essential technological and infrastructural changes required for the generalization of graphene may be sidelined. Conversely, a collective commitment to transformative change could accelerate progress across all dimensions, thereby facilitating the generalization of graphene in EESDs. Therefore, a better understanding of current priorities among different actors can offer valuable insights into whether and to what extent these priorities are in line with the future progress needed for the generalization of graphene.

One of the primary dimensions where progress is essential is the realization of the transformative functions that graphene can bring to EESDs (Arvidsson and Sandén, 2017; Döscher et al., 2021; Döscher and Reiss, 2021; Gumfekar, 2018; Olabi et al., 2021; Raccichini et al., 2015). Embedding graphene in EESDs offers a spectrum of benefits that touch upon diverse facets of EESDs. For example, it can lead to a notable reduction in waste (**P1**) (**CPP1**) (**RPP1**), primarily attributed to the enhanced longevity of EESDs (Arvidsson and Sandén, 2017; Olabi et al., 2021). It can also offer material advantages as graphene stands out as a promising candidate to replace critical and scarce materials (**P2**) (**CPP2**) (**RPP2**), addressing a pressing concern in the EESD domain (Arvidsson et al., 2016; Arvidsson and Sandén, 2017). Furthermore, the embedding

of graphene could alleviate socio-political concerns (P3) (CPP3) (RPP3) associated with some materials traditionally used in EESDs (European Commission, 2020a, 2020b). Finally, graphene could render EESDs a competitive edge, positioning them as a more sustainable alternative to existing (P4) (CPP4) (RPP4), unsustainable technologies (Olabi et al., 2021).

Another dimension pertains to the technical complexities of its production methods, involving trade-offs that influence its viability (Bøggild, 2018; Kauling et al., 2018; Levchenko et al., 2016; Raccichini et al., 2015; Seibers et al., 2020; Shapira et al., 2016). While certain production techniques offer scalability (P5) (CPP5) (RPP5) and cost benefits (P6) (CPP6) (RPP6), they often compromise the quality of the graphene produced. Despite advancements, cost-effective mass production remains elusive, with some anticipating breakthroughs in new synthesis methods (Shapira et al., 2016). The market is rife with graphene materials that, while commercially available, grapple with quality and reproducibility challenges (P7) (CPP7) (RPP7), directly impacting their efficacy in EESDs (Gonçalves et al., 2022; Kauling et al., 2018). Moreover, the generalization of current graphene materials into EESDs is hampered by their limited processability (or dispersibility) (P8) (CPP8) (RPP8) (Seibers et al., 2020).

A third critical dimension involves the embedding of such an advanced material into existing systems (Braun and Skinner, 2007; Huang et al., 2018, 2021; Sholl and Lively, 2016; Walton and Sholl, 2017). This embedding entails a series of infrastructural and procedural adjustments. Producers of EESDs will need to adapt to new graphene handling techniques (P9) (CPP9) (RPP9), a transition that might initially lead to a surge in manufacturing costs. Additionally, the production of graphene-based EESDs calls for specialized equipment (P10) (CPP10) (RPP10). These tools, often associated with high costs, require tailored adjustments, and their availability can be region-specific. Beyond these, the generalization of graphene entails a reevaluation and potential revamp of established norms and protocols, especially in the realms of storage (P11) (CPP11) (RPP11) and transportation (P12) (CPP12) (RPP12).

### 3. Methodology

Operating under the premise that the generalization of graphene in EESDs could represent a transformative change in the energy storage sector, our study takes a future-oriented multidisciplinary approach. Our aim is to explore to what extent current efforts (regarding the identified dimensions in Section 2.1) will indeed lead to significant progress (in the next two decades) that is needed for the generalization praxis. Therefore, we operate under several guiding assumptions that inform our methodological choices:

- The complex and diverse nature of the topics surrounding the generalization of graphene demands a diverse and integrative methodological palette. Therefore, we combine the Delphi technique with in-depth interviews to encompass the varied elements of this research. This allows us to ensure an encompassing perspective of the numerous aspects pertaining to our research objective, offering a richer spectrum of insights, and enhancing the rigor and depth of our inquiry.
- We recognize the inherently dynamic and unpredictable contours of the future and presume a current scarcity of consolidated knowledge regarding the generalization of graphene. The prevalent unpredictability and fluidity in projections highlight the need for robust methodologies. Hence, our choice of the Delphi method is methodically reasoned as it thrives in navigating uncertainties and ambiguities, transforming individual expertise into collective foresight, allowing us to gain insights into the complexities that are both in-depth and anticipatory.
- Acknowledging the diverse spectrum of actors within the graphene ecosystem, we are mindful that the mixture of industry actors (both

graphene and EESDs producers), and researchers (in academia and private sector) yields diverse perspectives, objectives, and strategies relative to the generalization of graphene. This acknowledgment shapes our intentional strategy to embrace a broad spectrum of participants in our Delphi rounds and personal interviews.

- Our approach is deeply tangled with a thoughtful consideration of time, and we postulate that the current aspirations and activities of stakeholders might not synchronize with the enduring objectives essential for the generalization of graphene in EESDs over the next two decades. This temporal dimension is not merely a background element but is a central dimension of the main aim of our study: to untangle not only how progress is being prioritized presently but also to articulate strategic pathways and prioritizations that are coherent with the anticipated transformative changes.

Guided by these assumptions, we configured our study as a Delphi-based scenario analysis, a methodology with a proven track record in capturing insights about future landscapes (Cairns and Wright, 2018; Landeta and Barrutia, 2011; Mayor et al., 2016; Melander, 2018; Okoli and Pawlowski, 2004; Rowe and Wright, 2011; Vernon, 2009). This methodology facilitates the construction of potential scenarios that serve as vessels to encapsulate diverse portrayals of conceivable futures, mirroring varied perspectives (van Notten et al., 2003). Our methodology hinges on the collective intelligence distilled from a panel of experts subjected to iterative rounds of questionnaires, refining collective understanding with each interaction.

The Delphi technique contributes to mitigating the social complexities emanating from hierarchical or personality disparities in collaborative contexts, thereby enabling a conducive environment for collective learning (Cairns and Wright, 2018). The process initiates with experts individually navigating through a questionnaire, succeeded by consolidation of responses which are then reverberated back to the participants. This reflection phase empowers experts to reassess their initial responses and to elaborate further. Iterations continue until a harmonious consensus or a stable state of responses emerge, which typically occurs a couple of rounds (von der Gracht, 2012).

Adhering to the methodological guidelines proposed by Nowack et al. (2011) and drawing inspiration from analogous endeavors (e.g., Culot et al., 2020; Jiang et al., 2017; Peppel et al., 2022), we immersed our panel of experts in evaluating a collection of formulated projections. These are succinct future theses, crafted by our research ensemble through a structured developmental process. The time horizon for our evaluation was consciously set for the year 2041.

The selection of a two-decade time horizon for this Delphi-based scenario development is grounded in contemplation of existing literature, focusing on the energy sector (Gross et al., 2018; Smil, 2017; Sovacool, 2016). Given the intrinsic complexity of technologies such as graphene and its application in EESDs, a shorter timeframe (than two decades) would likely be insufficient to encompass the substantive transformations and paradigm shifts. Consequently, a time horizon of two decades is posited as being conducive to providing a comprehensive and better understanding of the prospective developments in the generalization of graphene.

#### 3.1. Delphi study and data generation

We structured our Delphi study in a stepwise process. Initially, we began by conducting a series of 23 interviews, each formulated to cross-validate our initial identification of the determinants that are influencing the generalization of graphene in EESDs. These interviews, varying in duration from 45 min to 2 h, served as the introductory foundation for our study, aiding in the precise framing of our Delphi questionnaire, improving our initial interpretations of the determinants, expanding our participants' pool, and providing our Delphi results with contextual richness and relevance.

Advancing forward, insights generated from these initial interviews



served as input, enabling us to sharpen and categorize the projections into three coherent and logical clusters. This exercise facilitated the formulation of twelve empirically grounded projections, crucial to our Delphi survey and detailed in Table 1. The projections also formed the first section of the Delphi survey and were displayed as follows:

*“Please assess the progress you expect will be made in the upcoming 20 years in order to mainstream graphene in electrochemical energy storage devices.”*

Given the foundational assumption about the potential incongruities between the current predispositions of stakeholders and the sustained objectives as critical for the generalization of graphene in EESDs, an exploration of the current and optimal prioritization of each determinant within the projections became necessary. After the unveiling of projections in Table 1, we engaged our panel in a reflective assessment of the prioritization of projections, as outlined in Table 2.

*“Please assess the priority level you believe is currently assigned (marked by actual), and in contrast, the priority level you believe should be assigned (marked by desirable) to mainstream graphene in electrochemical energy storage devices.”*

**Table 1**  
Projections for generalization of graphene in EESDs.

Code.	Projections for the next 2 decades	Category	Source
P1.	In the next 20 years, I expect progress in reducing waste.	Transformative functions	Expert interviews
P2.	In the next 20 years, I expect progress in reducing reliance on critical materials.	Transformative functions	Expert interviews, (Arvidsson and Sandén, 2017)
P3.	In the next 20 years, I expect progress in fostering competition with unsustainable technologies.	Transformative functions	Expert interviews, (Olabi et al., 2021)
P4.	In the next 20 years, I expect progress to alleviate socio-political concerns.	Transformative functions	Expert interviews, (Arvidsson and Sandén, 2017; European Commission, 2020a; Olabi et al., 2021)
P5.	In the next 20 years, I expect progress to improve the quality of graphene.	Technical viability	Expert interviews, (Kauling et al., 2018)
P6.	In the next 20 years, I expect progress to improve the processability of graphene.	Technical viability	Expert interviews, (Lin et al., 2019)
P7.	In the next 20 years, I expect progress in the scalability of graphene.	Technical viability	
P8.	In the next 20 years, I expect progress to improve the prices of graphene.	Technical viability	Expert interviews, (Shapira et al., 2016)
P9.	In the next 20 years, I expect progress to align transport configurations.	Reconfiguration	
P10.	In the next 20 years, I expect progress to align handling configurations.	Reconfiguration	Expert interviews, (Behrens et al., 2017; Braun and Skinner, 2007; Huang et al., 2018)
P11.	In the next 20 years, I expect progress to align equipment configurations.	Reconfiguration	
P12.	In the next 20 years, I expect progress to align storage configurations.	Reconfiguration	

Then, we used the last three of the 23 preliminary interviews to act as pilot sessions, for our Delphi survey, with a focused intent on fostering clarity and mutual understanding. In our pursuit to refine the questionnaires' articulations and inquiries, we intentionally integrated the Qualitative Pretest Interview (QPI) method into our approach (Buschle et al., 2021). We adopted the QPI method to address the challenges of subjectivity and reflexivity in the formulation of Delphi statements and questions (Andersen, 2022; Markmann et al., 2021; Schmalz et al., 2021). It allows us to unpack the formulation of the Delphi statements and questions, seeking to understand and mitigate any sources of difficulty, ambiguity, or misinterpretation. Here, our interviewees were recognized as co-experts and collaborators in a joint endeavor to explore and explain the intended meanings and implications of each Delphi question or statement. This meant engaging in dialogic clarifications and fostering an intersubjective understanding, a shared, mutually constructed comprehension of the survey's components. Our objective, here, was to refine and optimize our survey's components based on the valuable insights and feedback obtained from these QPI sessions.

Subsequently, we administered the Delphi survey in two successive rounds, using Google Forms and employing a 5-point scale, a decision informed by the insights from our QPI's, to avoid respondent discomfort. Here, our emphasis on the term “desirable” aimed at capturing the subjective perceptions of the respondents (i.e., how “the experts” believed they should be prioritized instead of what “each item” demands in itself).

Following the initial round, an intermediate analysis facilitated the sharing of collective insights with all panelists, prompting them to reassess their responses considering the overarching consensus. This iteration allowed panelists to express concordance or discordance with the dominant perspectives in the subsequent round. Concluding our methodology, five additional interviews after Delphi's second round were conducted to cross-validate our findings, offering a sound exploration of subjective assessments and cross-validating our interpretation of the outcomes.

### 3.2. Participants

Initially, we used purposive sampling as a tactic to recruit the Delphi panelists (Patton, 2002). This facilitated the recruitment of panelists across diverse stakeholder realms, concentrating on their knowledge and expertise (van Audenhove and Donders, 2019). We channeled our focus towards three crucial stakeholder groups: graphene producers/suppliers, EESDs developers/producers including original equipment manufacturers, and researchers in both academic and non-academic entities. We further enhanced our expert pool through a cascading referral mechanism, asking interviews to recommend new panelists (Alon et al., 2019; Cairns and Wright, 2018).

However, our journey was punctuated with impediments, primarily stemming from the multidisciplinary essence of our study, leading to a reluctance among certain experts owing to the specialized nature of some domains. Despite concerted efforts, representatives from the policy domain were noticeably absent, citing a lack of proficiency in the technical dimensions of our inquiry. Additionally, confidentiality concerns surfaced as a daunting barrier, particularly among private actors, which required clear guidelines that guaranteed anonymous participation.

Our panel, detailed in Table 3, comprised 25 experts, with diverse geographical representations and an average of twelve years of experience. Despite the relatively smaller panel size, we enriched the reliability of our findings through robust cross-validation checks, such as the use of multiple sources of data (Levitt et al., 2018; Morrow, 2005). In any case, the panel dimensions align with the recommended frameworks for Delphi inquiries (Cairns and Wright, 2018; Okoli and Pawlowski, 2004).

Prior to the Delphi survey, we engaged in in-depth interviews with 28 experts, 16 of whom participated in the Delphi Survey. As explained

**Table 2**  
Actual and required priority levels of determinants.

Projection items	Code								
Reduce waste	Actual priority level	(CPP1)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP1)	Very low	1	2	3	4	5	Very high
Reduce reliance on critical materials	Actual priority level	(CPP2)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP2)	Very low	1	2	3	4	5	Very high
Foster competition with unsustainable technologies	Actual priority level	(CPP3)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP3)	Very low	1	2	3	4	5	Very high
Alleviate socio-political concerns	Actual priority level	(CPP4)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP4)	Very low	1	2	3	4	5	Very high
Improve quality	Actual priority level	(CPP5)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP5)	Very low	1	2	3	4	5	Very high
Improve scalability	Actual priority level	(CPP6)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP6)	Very low	1	2	3	4	5	Very high
Improve prices	Actual priority level	(CPP7)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP7)	Very low	1	2	3	4	5	Very high
Improve processability	Actual priority level	(CPP8)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP8)	Very low	1	2	3	4	5	Very high
Align transport configurations	Actual priority level	(CPP9)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP9)	Very low	1	2	3	4	5	Very high
Align handling configurations	Actual priority level	(CPP10)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP10)	Very low	1	2	3	4	5	Very high
Align equipment configurations	Actual priority level	(CPP11)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP11)	Very low	1	2	3	4	5	Very high
Align storage configurations	Actual priority level	(CPP12)	Very low	1	2	3	4	5	Very high
	Desirable priority level	(RPP12)	Very low	1	2	3	4	5	Very high

**Table 3**  
Delphi panelists ( $n = 25$ ) by years of experience, country, and stakeholder type.

Years of experience	Country	Stakeholder group
<8 years: 6	Australia: 1	Researcher: 13
8–15: 12	Canada: 1	Graphene producer/supplier;EESDs
16–23: 3	Germany: 3	developer/producer;Researcher: 1
>23 years: 4	India: 2	EESDs developer/producer: 3
	Italy: 1	EESDs developer/producer;Researcher: 1
	Norway: 2	Graphene producer/supplier: 5
	Spain: 6	Graphene producer/supplier;Researcher: 2
	Sweden: 3	
	United Kingdom: 5	
	United States: 1	

earlier, we conducted 23 interviews initially, plus five interviews after the second Delphi round, extending the breadth and depth of our understanding of the results. A detailed description of the profiles of our interviewees is available in [Appendix 1](#). The Delphi survey was structured across two rounds, with a minor attrition of six panelists in the second round. Following the guidelines from [Landeta and Barrutia \(2011\)](#), we integrated the insights of these panelists into the final analysis, considering their first-round responses as definitive.

### 3.3. Data analysis

The data analysis stage was structured to examine the results in a three-tiered manner, encompassing the description of results using descriptive statistics, the development of scenarios, and the construction of thematic and synthetic indicators addressed for the ideal scenario.

#### 3.3.1. Descriptive statistics

Initially, the survey results were analyzed through descriptive statistics, a standard procedure in Delphi studies, with a particular emphasis on mean values to interpret panelists' assessments. Panelists, first, assessed the projections for the next two decades. Then, they also evaluated the current priority levels assigned to the projections and, in contrast, the priority levels they deemed necessary. All assessments were based on a 5-point scale questions. We used the standard deviation (SD)

as a measure of consensus, where an  $SD \leq 1$  represented the consensus threshold ([von der Gracht, 2012](#)).

#### 3.3.2. Scenario development

We constructed three scenarios by hierarchically clustering the experts' assessments, as illustrated in [Fig. 2](#). Starting from the present, we envision three scenarios, with the current prioritization at the base, followed by the anticipated projections for the subsequent two decades, and the ideal prioritization at the apex, each explained with prospective interview data from the interviews, rendering them as prospective depictions of the future. We name these three hierarchies as current state scenario, projected state scenario, and ideal state scenario. 'Current state' scenario is grounded in the current prioritization of projections and offers a baseline understanding of the status quo. It serves as a reference point, highlighting the existing gaps and opportunities in the generalization of graphene in EESDs. 'Projected state' scenario draws from the expert panels' expectations for the next two decades. A hybrid of this scenario and the current state scenario paints a picture of the anticipated evolution of graphene's role in EESDs. 'Ideal state' is positioned as the pinnacle; this scenario embodies the optimal path for the generalization of graphene in EESDs. It is a manifestation of the desired future, where the full potential of graphene is realized, driving transformative change in EESDs.

#### 3.3.3. Construction of synthetic indicators

As the panelists evaluated both the current and the required priority levels they believed should be assigned to each item, we constructed several synthetic indicators based on this assessment. The objective of these synthetic indicators is to explore how the current aspirations and activities of various stakeholders can be aligned with the enduring objectives essential for the generalization of graphene in EESDs. Essentially, our ambition was to provide concrete implications on how to enable the pursuit of an ideal state scenario.

First, we constructed a thematic indicator based on the disparity between these current and required priority levels, which we refer to as "Priority Sufficiency Gap" and symbolized it as ( $T_i$ ). The scores of a ( $T_i$ ) for questions based on a 5-point scale have a distinct range ( $-4 \dots 0 \dots 4$ ). This range results from the subtraction of the required priority levels from the current priority levels, and operates on conditional rules, interpreted as follows:

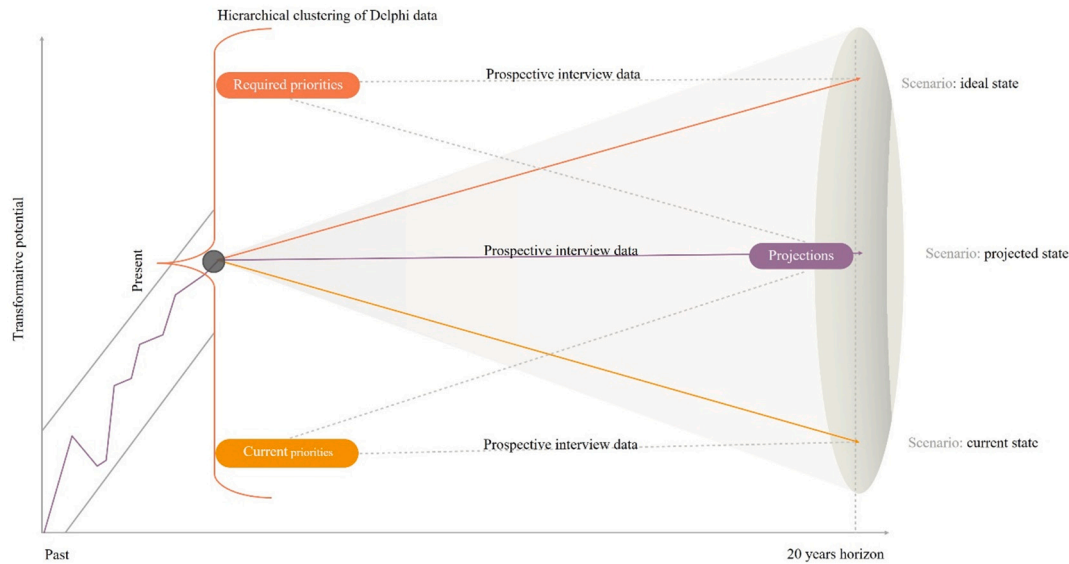


Fig. 2. Funnel illustration of scenario construction.

- i. If  $(T_i) < 0$  reflects under-prioritized
- ii. If  $(T_i) > 0$  indicates adequate prioritized
- iii. If  $(T_i) = 0$  denote optimal prioritized

Following the construction of the thematic indicator, we derived a synthetic indicator, “Priority Adjustment Index” and symbolized it as  $(S_i)$ , by normalizing the values of the first two conditions of the  $(T_i)$ . This normalization reinterprets “under-prioritization” as “urgency for action,” while “adequate prioritization” denoted “opportunity to foster favorable conditions.” Here, values proximate to zero suggest minimal impact, whereas those nearing 1 imply substantial impact. For the values of  $(S_i)$ , our focus was confined within the  $\geq 2$  and  $\leq 8$  range, recognizing the characteristic subjectivity and complexity, thereby deeming the extreme values of 0 and 1 as untenable. We used a unity-based normalization formula employed for developing  $(S_i)$  standardized values relative to the worst performer, setting the worst at 0 and the best at 1 (Akanbi et al., 2015, p. 52; Freudenberg, 2003, p. 10). The formula is provided in Eq. (A.1).

#### 4. Results

The analysis of the experts' assessments for the twelve projections, labeled as **P1** to **P12**, is outlined in Table 4. Concurrently, Table 5 synthesizes experts' assessments for the current prioritizations (**CPP1** to

**CPP12**) and the required prioritizations (**RPP1** to **RPP12**) along with the corresponding indicators (as formulated in Section 3.3.3).

##### 4.1. Consolidated analysis of projections and prioritizations

In the initial quartet of projections, **P1** to **P4**, focused on the transformative functions experts expect low progress with significant under-prioritization. For **P1**, a mean progress of 3.0 is expected in round 2. The current priority, **CPP1**, stands at 2.1, contrasting sharply with the required priority, **RPP1**, at 3.3. This difference yields a Priority Sufficiency Gap ( $T_1$ ) of  $-1.2$ , indicating under-prioritization and suggesting urgency for action based on the Priority Adjustment Index ( $S_1$ ). Similarly, **P2**'s mean progress in round 2 is anticipated at 3.0. With **CPP2** at 2.0 and **RPP2** at 3.6, the  $(T_2)$  is  $-1.6$ , again highlighting under-prioritization and an urgent need for intervention per the  $(S_2)$ . Nevertheless, any action is unlikely to be result in any as it is so high that it is virtually impossible to address. For **P3**, **CPP3** stands at 2.4 compared to **RPP3** at 3.9. With a mean progress of 2.8 expected in round 2, the resulting  $(T_3)$  is  $-1.5$ , reinforcing the pattern of under-prioritization and corresponding urgency indicated by the  $(S_3)$ . Lastly, **P4**, with **CPP4** at 2.0 and **RPP4** at 3.2, and an expected mean progress of 2.8 in round 2, yields a  $(T_4)$  of  $-1.2$ , emphasizing under-prioritization and the call for urgent action as indicated by the  $(S_4)$ .

Transitioning to the middle projections, **P5** to **P8**, which focus on technical aspects, experts foresee substantial advancements. **P5**, with a projected mean progress of 4.0 in round 2, **CPP5** at 3.2, and **RPP5** at 4.0, presents a  $(T_5)$  of  $-0.8$ . However, the  $(S_5)$  points to a relatively minimal impact. Continuing, **P6**'s **CPP6** is 3.1, while **RPP6** is 4.3, and a mean progress of 4.1 is expected in round 2. The resulting  $(T_6)$  is  $-1.2$ , and the  $(S_6)$ . Similarly, **P7**, with **CPP7** at 3.1 and **RPP7** at 4.2, is expected to have a mean progress of 4.2 in round 2. This translates to a  $(T_7)$  of  $-1.1$ , and the  $(S_7)$  affirms the urgency. For **P8**, **CPP8** at 2.9 is significantly lower than **RPP8** at 4.4 in round 2, leading to a  $(T_8)$  of  $-1.5$  and an ensuing call for action as indicated by the  $(S_8)$ .

Lastly, for the final set of projections, **P9** to **P12**, focused on practical implementations, the story unfolds consistently. **P9**, with **CPP9** at 2.4 and **RPP9** at 4.0, shows a mean of 3.5 in round 2, a  $(T_9)$  of  $-1.6$ , and an urgency for action via the  $(S_9)$ . However, the  $(S_9)$  has a remarkably high impact that is virtually impossible to address and thus may remain a challenge in the future. **P10** has **CPP10** at 2.3 and **RPP10** at 3.4, with a mean progress of 3.4 expected in round 2. This corresponds to a  $(T_{10})$  of  $-1.1$  and the  $(S_{10})$  underscoring urgency. **P11** presents **CPP11** at 2.4 and

Table 4  
Projections for generalization of graphene in EESDs.

Code	1- low progress to 5- high progress	Round 1		Round 2	
		Mean	SD	Mean	SD
P1.	Reduce waste	2.6	1.45	3.0	1.19
P2.	Reduce reliance on critical materials	2.6	1.35	3.0	1.06
P3.	Foster competition on non-sustainable technologies	2.8	1.21	2.8	<b>0.97<sup>a</sup></b>
P4.	Ease socio-political concerns	2.4	1.29	2.8	<b>1.00</b>
P5.	Improved quality	3.8	<b>0.99</b>	4.0	<b>0.93</b>
P6.	Improved processability	4.0	<b>0.89</b>	4.1	<b>0.83</b>
P7.	Improved scalability	4.2	<b>0.80</b>	4.2	<b>0.71</b>
P8.	Improved prices	3.5	1.04	3.7	<b>0.78</b>
P9.	Aligned with transport configurations	3.3	<b>0.96</b>	3.5	<b>0.88</b>
P10.	Aligned with handling configurations	3.3	<b>0.90</b>	3.4	<b>0.88</b>
P11.	Aligned with equipment configurations	3.5	1.04	3.6	<b>0.94</b>
P12.	Aligned with storage configurations	3.5	<b>0.93</b>	3.5	<b>0.83</b>

<sup>a</sup> SD in bold indicates consensus is reached.

**Table 5**  
Current and required priority levels of determinants.

1 - low priority to 5 - high priority		Code/ symbol	Round 1		Round 2	
			Mean	SD	Mean	SD
Reduce waste	Desirable	(RPP1)	2.8	1.25	3.3	<b>0.94<sup>a</sup></b>
	Actual	(CPP1)	2.2	1.2	2.1	<b>0.97</b>
	Under-prioritized	(T <sub>1</sub> )	−0.6		−1.2	
	Requires urgent action	(S <sub>1</sub> )	0.3		0.4	
Substitute critical materials	Desirable	(RPP2)	2.9	1.55	3.6	1.22
	Actual	(CPP2)	2	1.22	2	<b>0.96</b>
	Under-prioritized	(T <sub>2</sub> )	−0.9		−1.6	
	Requires urgent action	(S <sub>2</sub> )	0.6		<i>1<sup>b</sup></i>	
Spur competition with non-sustainable applications	Desirable	(RPP3)	3.3	1.34	3.9	<b>0.97</b>
	Actual	(CPP3)	2.6	1.33	2.4	<b>0.96</b>
	Under-prioritized	(T <sub>3</sub> )	−0.7		−1.5	
	Requires urgent action	(S <sub>3</sub> )	0.4		0.8	
Ease socio-political challenges	Desirable	(RPP4)	2.8	1.35	3.2	1.04
	Actual	(CPP4)	2.2	1.21	2	<b>0.82</b>
	Under-prioritized	(T <sub>4</sub> )	−0.6		−1.2	
	Requires urgent action	(S <sub>4</sub> )	0.3		0.5	
Improve quality	Desirable	(RPP5)	3.7	<b>0.89</b>	4	<b>0.61</b>
	Actual	(CPP5)	3.2	1.14	3.2	<b>0.85</b>
	Under-prioritized	(T <sub>5</sub> )	−0.5		−0.8	
	Requires urgent action	(S <sub>5</sub> )	0.2		0	
Improve scalability	Desirable	(RPP6)	4	1.1	4.3	<b>0.85</b>
	Actual	(CPP6)	3.3	1.31	3.1	<b>0.95</b>
	Under-prioritized	(T <sub>6</sub> )	−0.7		−1.2	
	Requires urgent action	(S <sub>6</sub> )	0.5		0.5	
Improve processability (dispersibility)	Desirable	(RPP7)	3.9	1.04	4.2	<b>0.85</b>
	Actual	(CPP7)	3.1	1.2	3.1	<b>0.95</b>
	Under-prioritized	(T <sub>7</sub> )	−0.8		−1.1	
	Requires urgent action	(S <sub>7</sub> )	0.5		0.3	
Improve prices	Desirable	(RPP8)	4.3	<b>0.9</b>	4.4	<b>0.91</b>
	Actual	(CPP8)	3.2	1.25	2.9	<b>0.97</b>
	Under-prioritized	(T <sub>8</sub> )	−1.1		−1.5	
	Requires urgent action	(S <sub>8</sub> )	0.9		0.9	
Aligning handling practices	Desirable	(RPP9)	3.8	<b>0.92</b>	4	<b>0.72</b>
	Actual	(CPP9)	2.5	1.1	2.4	<b>0.91</b>
	Under-prioritized	(T <sub>9</sub> )	−1.3		−1.6	
	Requires urgent action	(S <sub>9</sub> )	1		0.9	
Aligning equipment configuration	Desirable	(RPP10)	3	1.21	3.4	1.1
	Actual	(CPP10)	2.5	1.18	2.3	<b>0.83</b>
	Under-prioritized	(T <sub>10</sub> )	−0.5		−1.1	
	Requires urgent action	(S <sub>10</sub> )	0.3		0.4	
Aligning storage practices	Desirable	(RPP11)	3.2	1.26	3.7	<b>0.95</b>
	Actual	(CPP11)	2.5	1.19	2.4	<b>0.9</b>

**Table 5 (continued)**

1 - low priority to 5 - high priority		Code/ symbol	Round 1		Round 2	
			Mean	SD	Mean	SD
Aligning transport practices	Under-prioritized	(T <sub>11</sub> )	−0.7		−1.3	
	Requires urgent action	(S <sub>11</sub> )	0.4		0.6	
	Desirable	(RPP12)	3	1.35	3.5	1.06
	Actual	(CPP12)	2.2	1.15	2.2	<b>0.8</b>
	Under-prioritized	(T <sub>12</sub> )	−0.8		−1.3	
	Requires urgent action	(S <sub>12</sub> )	0.5		0.7	

<sup>a</sup> SD in bold indicates consensus is reached.

<sup>b</sup> Italic indicates values for (S<sub>1</sub>) falling outside of the established range.

**RPP11** at 3.7, with a mean progress of 3.5 expected in round 2, resulting in a (T<sub>11</sub>) of −1.3 and the respective urgency denoted by the (S<sub>11</sub>). Finally, **P12**, with **CPP12** at 2.2 and **RPP12** at 3.5, and an expected mean progress of 3.5 in round 2, concludes with a (T<sub>12</sub>) of −1.3 and the echoing urgency from the (S<sub>12</sub>).

#### 4.2. Scenarios

Following the structured approach set forth in Section 3.3, the following sections will unveil the distinct scenarios, each representing different facets and potentials of graphene in EESDs.

##### 4.2.1. Scenario 1: current state scenario

This scenario offers a baseline understanding of the *status quo*, serving as a reference point to highlight existing challenges and opportunities in the generalization of graphene. It envisions a future where significant progress occurs in the upcoming two decades around the technical determinants, along with incremental advancements in the reconfiguration of existing arrangements, despite a slightly pessimistic expansion of transformative functions.

A defining feature of this scenario is the endeavor to bring solutions to scale by challenging incumbent technologies. As one expert commented: “*right now already graphene is everywhere, but it is almost useless without achieving the required performance in EESDs.*” Another expert added: “*You have to count at the companies producing pristine graphene. I can certainly tell you the number is zero.*” Also, along the same lines, one expert said: “*There are zero companies producing graphene.*” Emphasizing incremental progress in current manufacturing methods as well as the development of new ones for graphene derivatives. This progress would allow for significant scalability, making graphene materials, to some extent, driving down production costs. However, the cost-effectiveness of graphene materials over the next two decades remains a subject of debate among experts.

The reconfiguration of incumbent arrangements is anticipated to occur gradually, starting from auxiliary equipment and handling practices. “*Graphene will create more opportunities, and this will lead us to develop new production methods and solutions and that could result in improvements,*” another expert noted, highlighting the potential for new actors producing graphene-enhanced EESDs to enter the ecosystem with configurations already aligned with the needs and requirements of graphene materials. However, the cost associated with these reconfigurations is a significant barrier, influencing the decision-making of incumbent actors who may opt not to consider reconfiguring these arrangements.

Despite the advancements in technical determinants, the diffusion of graphene in EESDs is unlikely to allow the transformative functions to materialize significantly. “*I expect graphene to be everywhere in EESDs in*



the next two decades but as an additive providing incremental improvements to EESDs,” one expert stated, emphasizing the continued reliance on critical materials and the limited impact on reducing waste and alleviating socio-political concerns. The momentum created by these developments is expected to be insufficient to achieve the potential impact of the technology to address key transformative functions, requiring significant research and development efforts.

This scenario also foresees multiple actors participating in collective efforts to drive change, interacting at various levels to bring about solutions to scale and challenge incumbent technologies. *“The bigger you make the batteries the more functionality you get but that will always mean increases in weight and so you want to find materials [such as graphene] that are lighter or can provide you more with less,”* one expert commented, highlighting the potential for graphene to be used in niche applications to reduce the weight of EESDs or to improve mechanical and chemical properties of EESDs. However, the developments in this scenario are expected to be highly fragmented, focusing on the value of graphene compared to incumbent technologies, and may not achieve sufficient progress to enable graphene's full transformative potential.

#### 4.2.2. Scenario 2: projected state scenario

This scenario paints a picture of the anticipated evolution of graphene's role in EESDs over the next two decades, based on the experts' projections. It represents a future where advancements are expected to occur, reflecting the collective expectations of the expert panel for the upcoming two decades.

In this scenario, experts anticipate significant advancements in the technical determinants of graphene. The quality of graphene is expected to see substantial improvements, driven by enhanced interaction and refined production methods. An expert expressed: *“as we transition towards industrialization, I foresee significant enhancements in graphene's quality due to increased interaction and advancements in production methodologies.”* Another expert commented: *“Without the required quality, the performance in virtually every application can be compromised. Therefore, quality is a top priority not only for graphene producers but also for application developers.”* This progress is anticipated to facilitate the scalability of graphene, making it available in larger quantities and potentially reducing production costs. However, the experts also anticipate challenges in achieving cost-effectiveness and addressing processability issues over the next two decades. For example, an expert remarked: *“Most graphene materials we engineer are controlled in many ways and I don't expect that scale in the way you describe it easily in the next twenty years. I believe good quality graphene is challenging to deal with in battery producers because of dispersion and processability issues.”*

The projected state scenario foresees a gradual and controlled reconfiguration of incumbent arrangements within the EESD production ecosystem. New actors are expected to emerge, introducing innovative configurations aligned with the requirements of graphene materials. However, the high costs associated with these reconfigurations may pose challenges, influencing the decisions of incumbent actors and potentially limiting the entry of new ones. *“The reconfigurations required are substantial, and the associated costs may deter many incumbent actors from embracing them,”* an expert remarked.

While the diffusion of graphene in EESDs is expected to bring about improvements in the lifespan of EESDs and reduce reliance on critical materials, the realization of broader transformative functions remains uncertain. The experts project that the advancements in graphene will primarily serve as incremental improvements to existing EESD materials, without fully addressing the socio-political concerns related to reliance on critical materials. *“Graphene will likely serve as an additive, providing incremental improvements, but its potential to alleviate socio-political concerns remains questionable,”* commented one expert.

This scenario anticipates interactions between various levels and outcomes, with multiple actors participating in collective efforts to drive change. The advancements in graphene are expected to spark the development of niche applications and potentially expanding to other

areas. However, the experts believe that significant research and development efforts are required to achieve the potential impact of the technology on key transformative functions. The generalization of graphene in EESDs is expected to be fragmented, with the focus primarily on technical determinants and the value of graphene compared to incumbent technologies.

#### 4.2.3. Scenario 3: ideal state scenario

This scenario reveals the ideal path for the generalization of graphene in EESDs, depicting a future where graphene's full potential is realized, driving transformative changes and achieving broader systemic transformations in EESDs over the next two decades. Despite its plausibility, this scenario requires intensive efforts for it to unfold.

In this desired scenario, experts envision a future where significant advancements in the technical aspects of graphene are achieved. *“If the current limitations of existing devices are resolved, graphene could make energy storage devices a reasonable alternative to fossil technologies in the next ten to twenty years,”* an expert projected. The quality and scalability of graphene would reach ideal levels, allowing for a wider range of applications and making graphene materials more competitive relative to unsustainable technologies. Along these lines, an expert said: *“we may be able to produce graphene of reasonable quality and in large quantities in the upcoming ten years as we are seeing various efforts ranging from standards to new techniques and general interest from EESDs developers and policymakers.”* Another expert said: *“Quality depends on the requirements of the EESDs developers, and in most cases, it is possible to achieve it but reproducing the exact quality is a problem. I expect that in five to ten years we may see significant improvement in quality.”*

The ideal state scenario foresees extensive reconfigurations of incumbent arrangements and the emergence of new actors and configurations in the EESD production ecosystem. *“I can imagine that in the next five to ten years we will have made enough progress for these issues to be completely aligned,”* another expert stated. These reconfigurations would be substantial, overcoming the challenges and costs associated with the generalization of graphene materials.

The realization of graphene's potential would bring about discernible transformative functions, reducing waste and reliance on critical materials significantly. *“Graphene-enhanced EESDs would progressively become clearly more competitive and would also reduce waste,”* according to an expert. Another interviewee said: *“New policies would facilitate the generalization of graphene, as noted by an expert: “If a notable progress is made on the side of graphene, it could be that government policies may impose a quota on waste, where graphene may play an important role even with its current high prices.”* Several experts anticipate that the full realization of transformative functions would become fully visible in the next two decades, with graphene playing an important role in addressing socio-political concerns and contributing to the transition towards more sustainable technologies.

This scenario anticipates a harmonious interaction with strong coordination among diverse actors, leading to the resolution of collective dilemmas and substantial rearrangements in policies. *“We will see remarkable progress in the upcoming ten years thanks to many ongoing projects that will provide important data regarding the processability and will allow graphene producers to improve the processability of the materials,”* an expert conveyed. Another expert said: *“To have a reasonable processability, you need data on the interaction of graphene with other materials, which till now is very limited.”* The generalization of graphene in this scenario is expected to be widespread and beneficial at various scales, with graphene materials being ubiquitous and enabling the transition towards the electrification of the transportation sector.

## 5. Discussion

We constructed three scenarios for the generalization of graphene in EESDs. First, *current state* in which graphene has made notable technical advancements, but its transformative potential is limited to “nice-to-

have” functionalities. Second, *projected state* in which graphene's technical progress and adoption of “nice-to-have” functions in EESDs will continue, suggesting a gradual evolution. Third, *ideal state* in which graphene's technical barriers are surmounted and its transformative capacities are realized. Our findings indicate a likely trajectory for graphene generalization that combines elements from both the current and projected states over the next two decades. Overall, the findings suggest that graphene's the pursuit of transformative change depends on addressing strategic, technical, and systemic challenges.

Notably, the production of graphene and its derivatives is on a progressive trajectory in terms of scaling their production and, to a certain degree, enhancing their quality and dispersibility. However, significant barriers like quality remain (Kauling et al., 2018) and high costs, which have not reduced as anticipated (Shapira et al., 2016), mainly as a result of high production costs. The present materials' quality may be nearing its apex, as the disparity between the current and required priorities is marginal. Simultaneously, there is an overwhelming consensus that the current qualities of graphene materials are inappropriate for most applications (Bøggild, 2018; Kauling et al., 2018; Kovtun et al., 2019; Raccichini et al., 2015). In parallel to this challenge, the cost trajectory of graphene projects a persistent financial burden across imagined futures, adding layers of uncertainty. The unsettling equilibrium of cost-to-quality thus emerges as a potential burden, overshadowing graphene's promise compared to contemporary materials. This is likely to limit graphene's strategic relevance from exerting a ripple effect across societal levels. For example, performance reliability would severely erode trust in the technology and simultaneously high costs would make graphene-enhanced EESDs less competitive compared to alternatives using traditional materials.

Unexpectedly, another challenge is the irresistible focus on “nice-to-have” functions over transformative functions of graphene's use in EESDs, in contrast to an overwhelming consensus that graphene and its derivatives will drive transformative change (Arvidsson and Sandén, 2017; Döscher et al., 2021; Döscher and Reiss, 2021; Gumfekar, 2018; Olabi et al., 2021; Raccichini et al., 2015). These nice-to-have features refer to the mere fact that graphene is widely expected to be used as a niche application in EESDs, e.g., as a coating agent for battery electrodes. Meaning that the potential of graphene materials will be limited to elevating incumbent materials' performance. This skewed focus on nice-to-have functions over transformative functions could have several negative implications for the future of graphene. First, it could lead to developmental stagnation of graphene-based EESDs. Second, because of this overemphasis, the realization of the transformative potential of graphene in EESDs could be delayed. After all, such a trajectory misaligns with the principle of inclusivity and reach as it limits graphene's resonance across diverse stakeholder groups, potentially confining its benefits to a narrower spectrum. For example, overemphasis on nice-to-have functionalities means addressing problems that are not necessarily the most pressing or significant, which are influential on a global scale.

Beyond the functional focus, the reconfiguration of incumbent arrangements presents its own set of challenges. The task of reshaping these incumbent arrangements is marked by initial resistance to change. This anticipated inertia highlights the challenges graphene faces in its symbiotic relationship with existing systems, and the lack of capacity to restructure incumbent arrangements. For example, EESDs industry's entrenched interest in the incumbent system presents a vivid illustration of this inertia. For instance, the generalization of graphene in EESDs entails substantial changes, from overhauling supply chain practices to retraining personnel and tailoring auxiliary equipment. Additionally, the incumbent actors, who have significant influence and stakes in the status quo, might be resistant to such reconfiguration due to potential threats to their position or the need for substantial investments in new infrastructure. This could be one reason to explain the disparity in the current and required prioritization of these arrangements.

Drawing upon the concept of the generalization of innovation, it becomes evident that the generalization praxis is not instantaneous but

rather demands a significant temporal investment (Gross et al., 2018; Sovacool, 2016), reinforcing the notion of its evolutionary nature. Our analysis further underscores the challenges inherent in the EESD landscape, notably the discord stemming from a non-coordinated ecosystem. This lack of alignment and coordination, characterized by divergent stakeholder interests and strategic orientations, inevitably impedes the realization of the transformative potential that graphene promises for the EESD sector (Larrue, 2021). Under such circumstances, the promise of graphene in EESDs remains unfulfilled despite the existence of tangible nice-to-have applications.

Observing the very dynamics of graphene's generalization in EESDs, one is compelled to challenge the adequacy of conventional diffusion and scaling models. While such models provide insights into the spread and growth of innovations, they often overlook the interdependencies and complexities that advanced technologies, especially graphene, uniquely bear. For instance, certain narratives hail graphene as an “easy-to-scale solution,” tying its potential to broader sustainable development goals and societal challenges. Yet, these narratives may merely serve as a pretext to hasten the scaling of such innovations, possibly benefiting only a select few. Such a limited approach, focusing predominantly on industrialization and adoption, can be not only misleading but impede the transformative potential of innovation. In such a context, scaling or following traditional diffusion pathways offers a myopic vision, potentially leaving the wider pursuit of transformative change unaddressed. It is here that the broader, richer notion of “generalization” becomes essential, offering a comprehensive lens to harness graphene's transformative potential in an interconnected world.

All in all, this is neither to suggest that graphene and its derivatives may not be a viable solution in EESDs (Alvial-Palavicino and Konrad, 2019; Konrad and Alvial-Palavicino, 2017) nor to advocate it is on the right pathway to fulfill their promises (Reiss et al., 2019). Instead, it may require more than two decades for it to develop and be widely used in EESDs. For the next two decades, its promises in EESDs are mere supplementary functions (i.e., limited niche applications). Graphene derivatives, on the other hand, will play an important and yet limited role in EESDs. As for single-layered graphene, it will need more time than graphene derivatives, and perhaps one day it will be considered a non-scalable technology that only paved the way for the development of other two-dimensional materials.

Given the distinct challenges associated with graphene's generalization, the following implications are tailored to address the creation of enabling conditions for the generalization of graphene to materialize. First, the consistent production of graphene materials remains an alarming concern. To address this, regulatory bodies, in collaboration with leading research institutions specializing in graphene research and industry actors, should formulate and promulgate rigorous quality assurance standards, reiterating earlier calls for standardization (Bøggild, 2018; Kauling et al., 2018). These standards should encompass various criteria that describe the quality of the material, ensuring that graphene used in EESDs meets a benchmark of excellence. Second, industry actors should be cautious of over-relying on “nice-to-have” functionalities and look deeper into their transformative potential. This implies rethinking current prioritizations and addressing the prioritization sufficiency gap.

Third, broad R&D investments, while valuable, may not be sufficiently targeted to advance breakthroughs. We take inspiration from the business model of “vertical integration,” and advocate the establishment of “innovation hubs or consortia” that precisely simulate the idea of vertical integration. The reason why we advocate this is that there are a handful of successful companies producing graphene-enhanced technologies, but they have primarily been able to do so thanks to their in-house capabilities and resources, allowing them to exchange data and resources in real-time. By centralizing the entire innovation pipeline, idea generation, research, development, implementation, and regulation and standards, within one integrated ecosystem, such a hub could help address the inertia emerging technologies face due to the exchange

of information between graphene producers and EESD manufacturers, assuming their capacities and resources are different and cannot progress as standalone actors. This collaborative, all-encompassing approach may allow for the co-creation of adaptive frameworks that evolve alongside the innovation.

Fourth, recognizing the potential reconfiguration needed to enable smooth operations, industry consortia should craft protocols and best practices. These guidelines should focus on ensuring almost effortless operations of graphene and optimizing production processes while maintaining consistent quality standards. By identifying potential bottlenecks in sourcing, integrating, and quality-checking graphene, strategies can be developed to mitigate these challenges.

Reflecting upon our methodological approach, several limitations merit consideration. First, we used the first-round assessments of the six panelists who dropped out in the second. As their assessments remained unchanged in the subsequent round, other panelists may have leaned towards these assessments and created more consensus. Overall, we find that the Delphi method combined with in-depth interviews is a useful methodology to unpack key dynamics of the generalization praxis. Second, the complex, dynamic, and multifaceted nature of graphene's ecosystem means that no single methodological approach can capture all restraints, and our choice, though rigorous, may leave certain aspects of the landscape unexplored or oversimplified.

Given these limitations, we propose two future research avenues. First, it is crucial to explore the potential detrimental implications of graphene and its derivatives, juxtaposing them with their prospective advantages. Second, it is essential to scrutinize the spread of innovation benefits on a global scale. An important approach would be to operationalize the idea of “benefit” by examining the capacity of innovation to bring about sustainable solutions to societal problems, particularly under the context of the third frame innovation policy (Schot and Steinmueller, 2018). Nonetheless, such an operationalization would also be useful to discern potential technological dependencies and prospective risks and vulnerabilities inherent in the fourth frame innovation policy (Edler et al., 2023).

## 6. Conclusion

Graphene's trajectory in the domain of EESDs paints a portrait of innovation in the midst of contemporary societal challenges. While the material's groundbreaking potential is acknowledged, its prevailing application leans heavily towards augmentative, “nice-to-have” roles

rather than driving transformative change. This trend, coupled with the entrenched resistance from established arrangements, may inhibit graphene's path from reaching its transformative zenith. The stark divergence between its current applications and its idealized potential indicates that while technological breakthroughs are crucial, their “generalization” is equally, if not more, crucial. To achieve graphene's transformative capabilities, a synchronized effort, spanning policy, industry, and academia, is essential. Only through such a collaborative approach can graphene transition from its current state of enhancement to one of transformation.

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## CRedit authorship contribution statement

**Ali Haidar:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing, Visualization, Project administration, Funding Acquisition. **José Guimón:** Conceptualization, Methodology, Validation, Writing, Supervision, Project administration. **Ido Alon:** Conceptualization, Methodology, Visualization, Writing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

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## Appendix 1. List of interviewees

	Role/position	Type of organization	Country	Stakeholder group
1	Professor	University/related to two EU initiatives on graphene and battery materials	Sweden	Researcher
2	Professor	University	Sweden	Researcher
3	R&D manager	Large original equipment manufacturer	Germany	EESDs developer/user
4	Researcher	Large university-based center on graphene	United Kingdom	Researcher
5	Head of a department	National institute focused on graphene	United Kingdom	Researcher
6	Researcher	Large original equipment manufacturer	Germany	EESDs developer/user
7	Researcher	National institute focused on batteries cells	Germany	Researcher
8	Researcher	National materials institute	Spain	Researcher
9	Program manager	Program manager in EU led initiative	Italy	Researcher
10	Product manager	Medium-sized graphene supplier	Spain	Graphene producer
11	Innovator	Focused on the production of graphene and development of EESDs	USA/China	Graphene producer/EESDs developer
12	Head of a department	University Department focused on synthesizing GRMs and developing EESDs	Spain	Researcher
13	Director of a department	National center for renewable energies	Spain	EESDs developer/user
14	Researcher	National research center for electrochemical and thermal energy storage	Spain	Researcher
15	Senior researcher	State-owned research institute	Sweden	Researcher
16	Researcher	Research institute focused on developing graphene nanoparticles	Spain	Researcher
17	CEO	Medium-sized graphene producer/supplier	Spain	Graphene producer
18	Researcher	Large graphene producer	United Kingdom/ Sweden	Graphene producer

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	Role/position	Type of organization	Country	Stakeholder group
19	Program manager	Large graphene producer	United Kingdom	Graphene producer
20	Researcher	National institute focused on batteries cells	Germany	Researcher
21	Project manager	Medium-sized graphene producer/supplier	Spain	Graphene producer
22	Researcher	National research center for electrochemical and thermal energy storage	Spain	Researcher
23	Technology transfer	Medium-sized graphene supplier	Italy	Graphene producer
24	R&D	A large graphene producer	Spain	Graphene producer
25	Technology transfer	Medium-sized graphene producer/supplier	Italy	Graphene producer
26	Project manager	Medium-sized graphene producer/supplier	Italy	Graphene producer
27	Researcher	Large car manufacturer – battery cell technology	Germany	EESDs developer/user
28	Professor	Principle investigator	United Kingdom	EESDs developer

Formula used to construct the synthetic indicator.

$$S_i = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \quad (\text{A.1})$$

where:

- $X$  is the average of the differences between the desirable and actual scores for each driver and barrier
- $X_{\max}$  and  $X_{\min}$  are the minimum and maximum values of the mean of all differences.

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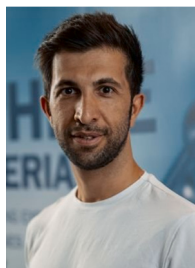


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