Energy for Sustainable Development 71 (2022) 279–290

Contents lists available at ScienceDirect

Energy for Sustainable Development

Mainstreaming graphene in electrochemical energy storage devices: A Delphi-based adaptive priority-setting

Bojan Ali Haidar [a,b,*], José Guimón [a], Javier Pérez Martínez [b]

[a] Research Group on Economics and Management of Innovation, Department of Development Economics, Universidad Autónoma de Madrid, Madrid, Spain
[b] Avanzare Innovación Tecnológica S.L., La Rioja, Spain

ARTICLE INFO

Article history:
Received 7 July 2022
Revised 2 September 2022
Accepted 2 October 2022
Available online xxxx

Keywords:
Impact at scale
Mainstreaming
Delphi method
Graphene
Electrochemical energy storage devices

ABSTRACT

Mainstreaming novel materials is essential to overcome crucial limitations of energy storage devices to address societal challenges and decarbonization efforts. However, mainstreaming requires enabling conditions that are influenced by complexities and tensions. Building on the concept of outcome-oriented scaling, this study explores how prioritization of interdependent drivers and barriers influences mainstreaming graphene in electrochemical energy storage devices. We capture the knowledge and perceptions of an expert panel through a Delphi survey combined with in-depth interviews. We find the ongoing prioritization trajectories to fail in setting interdependent drivers and barriers as a vision to achieve impact at scale, in creating opportunities to accelerate mainstreaming, and in addressing key sustainability pressures and reconfiguration barriers. Also, we find widespread consensus that urgent action is required to bend the prioritization trajectories in the right direction to achieve impact at scale. Mainstreaming graphene is likely to challenge, compete and disrupt incumbent systems instead of enabling a smooth transition.

Introduction

Efforts to electrify the transportation sector have led to an ever-increasing demand for high-performance energy storage technologies (Marinaro et al., 2020). Among the various energy storage systems, electrochemical energy storage devices (EESDs) are expected to play an important role in the electrification of the transportation sector (Burd et al., 2021; Sauer, 2015). EESDs include lithium-ion batteries and next-generation technologies, such as lithium-sulfur and metal-air batteries, as well as hybrid technologies (Gardner et al., 2016, p. 10). High-performance EESDs are critical to reducing dependency on unsustainable energy sources and enabling radical energy transitions (Ballinger et al., 2019).

However, EESDs may prove futile in transforming the transportation sector and facilitating radical energy transitions unless significant performance improvements are achieved to enhance their advantages relative to unsustainable technologies (Ballinger et al., 2019; How et al., 2022; Lach et al., 2018). Performance improvements depend on a combination of physical and chemical properties of the materials used in EESDs. It is, therefore, critical to accelerate the mainstreaming of novel materials in energy storage technologies (European Commission, 2020a; Hache et al., 2019; Huang et al., 2018; Koyamparambath et al., 2022; Sivaram et al., 2018).

Since the discovery of graphene in 2004, significant efforts have been made to deploy and disseminate its application in EESDs (Olabi et al., 2021; Racchichini et al., 2015). The interest in using graphene and its related materials (GRMs) in EESDs has been driven by its unique properties, such as chemical and thermal stability, light weight, large surface area, and electrical conductivity (Kakaei et al., 2019; Wu et al., 2012). GRMs stand to become predominant cathode materials for EESDs by significantly improving their performance through enhanced electrical conductivity (Boulanger et al., 2021; Liu et al., 2020; Moreno-Fernández et al., 2021; Peng et al., 2018), and sustainability and competitiveness through improved lifespan (Olabi et al., 2021; Racchichini et al., 2015). These benefits have been demonstrated to be technologically feasible in small-scale experiments. However, multiple challenges associated with manufacturing GRMs, and reconfiguring incumbent socio-technical arrangements still require more research to pave the way for mainstreaming.

The aim of this paper is to explore how the prioritization of interdependent drivers and barriers shapes the mainstreaming of GRMs in EESDs. We focus on the current prioritization trajectories and the extent

Abbreviations: GRMs, Graphene and its related materials; EESDs, Electrochemical energy storage devices; SD, Standard deviation.

* Corresponding author at: Research Group on Economics and Management of Innovation, Department of Development Economics, Universidad Autónoma de Madrid, Madrid, Spain.

E-mail addresses: abhaidar01@gmail.com (B.A. Haidar), jose.guimon@uam.es (J. Guimón), jperez@avanzare.es (J. Pérez Martínez).

https://doi.org/10.1016/j.esd.2022.10.004

to which they create a conducive environment for accelerating the mainstreaming GRMs in EESDs by identifying opportunities and tensions. We rely on a two-round Delphi survey combined with in-depth expert interviews to capture experts' perceptions and knowledge, aiming to inform policy design regarding the much-needed acceleration of GRMs in EESDs (U.S. Department of Energy, 2020; European Commission, 2020a; Huang et al., 2018, 2021). Our study is consistent with recent calls for more research that inspires improved approaches for accelerating the mainstreaming of new technologies to responsibly and inclusively address societal problems.

Accelerating outcome-oriented scaling

Conventional concepts of diffusion and adoption of innovation (Rogers, 1962) fall short in capturing the wickedness associated with the mainstreaming of innovations to address societal problems and anticipating sustainability implications (Biggi & Giuliani, 2021; Vargo et al., 2020). In contrast, the notion of outcome-oriented scaling addresses the inclusive acceleration of mainstreaming innovations by placing societal problems at the center of scaling initiatives and anticipating future implications (Ghiron et al., 2014; Wigboldus, 2016). Outcome-oriented scaling refers to inclusive and refined approaches and strategies through which innovation's outcomes are responsibly mainstreamed in society and contribute to broader systemic change processes to achieve impact at scale (Wigboldus, 2016; Wigboldus et al., 2016). Its purpose is to steer the outcomes of innovation toward societal problems by highlighting the idea that innovations and their mainstreaming in society are shaped by transformative social processes (Schut et al., 2020).

Scaling innovations typically encompasses two distinct approaches: push and pull scaling (Wigboldus et al., 2016). The push scaling approach is primarily technology-driven, presupposing that a novelty has a value that leads to benefits at scale. In this approach, scaling efforts are directed toward adoption and uptake, where the innovation competes, challenges, and disrupts the incumbent regimes. However, considering the path dependency and relative stability of incumbent regimes, push scaling may be ineffective in inducing innovations to achieve impact at scale.

Pull scaling, on the contrary, conceives multiple drivers and barriers as a desirable vision and stimulates enabling conditions to orchestrate scaling processes to achieve intended outcomes (Schut et al., 2020). The pull scaling approach focuses on reorienting system values toward the innovation such that the incumbent regime stimulates and accommodates the innovation, creating a self-organized dynamic. Pull scaling may be more compelling than push scaling in accelerating the achievement of impact at scale (i.e., mainstreaming). It leverages multiple interdependent drivers and barriers (Wigboldus et al., 2016) to create a process of spontaneous order (Leeuwis & Aarts, 2011) and opportunities (van Mierlo et al., 2013), leading to accelerated system transformation and mainstreaming of innovations. Nevertheless, the notion of pull scaling is far more convoluted as its orchestration arises from specific and coinciding events influencing multiple drivers and barriers (Hall & Dijkman, 2019). Accordingly, pull scaling requires continuous monitoring and adaptive management to facilitate innovations embedding in society (Arkesteijn et al., 2015; Klerkx et al., 2010).

We draw on the concept of pull scaling to accelerate the mainstreaming of innovations' outcomes and outputs and achieve impact at scale. Therefore, in the remainder of this section, we identify the drivers and barriers to mainstreaming GRMs in EESDs and discuss prioritization challenges regarding the drivers and barriers shaping the acceleration of scaling.

Drivers and barriers for scaling GRMs in EESDs

GRMs are a family of materials available in different forms, such as graphene films, graphene oxide, and reduced graphene oxide (Döscher et al., 2021; Döscher & Reiss, 2021). Thanks to their electrical and chemical properties, they are expected to resolve key technological issues in EESDs and help contribute to more sustainable modes of production and consumption (Olabi et al., 2021; Raccichini et al., 2015). On the one hand, various sustainability pressures and technological improvements drive the mainstreaming of GRMs in EESDs (Table 1). On the other hand, multiple technological trade-offs and reconfiguration barriers hinder the mainstreaming of GRMs (Table 1).

From the perspective of the drivers, there are two sets of drivers that stimulate the mainstreaming of GRMs in EESDs: external and internal drivers (Table 1). The external drivers are related primarily to key sustainability pressures that include environmental impact, socio-political and resource depletion concerns, and cost reduction (Castelvecchi, 2021; U.S. Department of Energy, 2020; European Commission, 2020b, 2021; Mauler et al., 2021; Olabi et al., 2021; Pavel & Blagoeva, 2017). For example, GRMs are expected to open new opportunities by lowering overall costs, minimizing waste, and reducing environmental impact. They are also expected to play a crucial role in substituting critical materials (Arvidsson & Sandén, 2017). For instance, graphite is a critical material but yet an essential component in EESDs that GRMs could replace (U.S. Department of Energy, 2020; European Commission, 2020b, 2021). Finally, the advances GRMs will unleash are expected to make current and future EESDs competitive compared to non-sustainable applications, e.g., fossil fuels (Olabi et al., 2021). Against this backdrop, such systems with sustainability pressures allow inducing systemic change relatively easier compared to stable systems (Williams, 2001) and hence allow for accelerated mainstreaming.

These external drivers depend on internal drivers, i.e., the improvements made in EESDs due to the use of GRMs. The internal drivers are associated with the improvements made in the electrochemical performance of EESDs, which relate to performance characteristics such as energy and power density, in addition to improving life cycle and overall safety (El-Kady et al., 2016; Ladrón-de-Guevara et al., 2019; Moreno-Fernández et al., 2020; Wong et al., 2018). These technological improvements are essential to overcome the limitations of current EESDs and offer potential solutions for next-generation devices.

However, there are two categories of barriers that hamper the mainstreaming of GRMs in EESDs: technological limitations and reconfiguration constraints (Table 1). Technological limitations are associated with the manufacturing techniques of GRMs (Du et al., 2019; Gumfekar,

Table 1
A taxonomy of drivers and barriers to mainstreaming GRMs in EESDs.

Category	Specific items	Reference
Drivers		
Internal drivers	Improve energy density	(Patel et al., 2020)
	Improve power density	(Lu et al., 2018)
	Increase lifespan	(Zhang et al., 2018)
	Improve safety	(Raccichini et al., 2015)
External drivers	Cost reduction	(Hassoun et al., 2014; Mauler et al., 2021)
	Waste reduction	Expert interviews
	Competition non-sustainable applications	(Olabi et al., 2021)
	Substituting critical materials	(Arvidsson & Sandén, 2017)
	Socio-political concerns	Expert interviews
Barriers		
Technological limitations	Quality	(Bøggild, 2018; Kauling et al., 2018)
	Processability	(Lin et al., 2019)
	Scalability	
	Price	(Shapira et al., 2016)
Reconfiguration barriers	Handling	(Behrens et al., 2017; Braun & Skinner, 2007; Huang et al., 2018; Lin et al., 2019)
	Equipment	
	Transport	
	Storage	

2018; Kong et al., 2019; Levchenko et al., 2016). Each production technique involves trade-offs between quality, price, processability, and scalability. Commercially available GRMs vary considerably not only between different GRMs producers but also between batches from a single producer (Kauling et al., 2018; Probst et al., 2015; Ye & Tour, 2019). Furthermore, the current prices of GRMs influence their economic accessibility and, therefore, their scaling (Burd et al., 2021). This is directly linked to the "cost-saving" driver mentioned above, and current prices can affect the mainstreaming efforts as well as the attempts to address societal challenges. After all, mainstreaming GRMs requires incorporating goals beyond "controlled" performance, such as volume, reproducibility, and production cost (Huang et al., 2018).

A key challenge lies in the availability and accessibility of specialized knowledge and equipment to reconfigure incumbent arrangements, specifically in periphery countries (Castrejon-Campos, 2022). The unavailability and inaccessibility of specialized knowledge and auxiliary equipment may influence mainstreaming and leads to disproportionate upscaling in core countries, leaving peripheral countries as followers and adopters (Castrejon-Campos, 2022). Such barriers have been widely recognized as infrastructure requirements constraints (Rosenthal et al., 2018). Accordingly, the second group of barriers relates to the existing arrangements, equipment, practices, and norms.

Incumbent arrangements of EESDs producers play an essential role in the mainstreaming of GRMs (Meelen et al., 2019). In particular, four elements require reconfiguration to pave the way for mainstreaming: auxiliary equipment, handling arrangements, storage practices, and associated transportation practices (Behrens et al., 2017; Braun & Skinner, 2007; Lin et al., 2019). These transformations are complex due to the "uniqueness" of the scaling of energy technologies (Braun & Skinner, 2007), which can lead to delays in their engineering and installation. In addition, they also imply significant cost increases for EESDs developers.

Method

In this study, we used a two-round Delphi survey combined with in-depth expert interviews. Delphi studies focus on eliciting experts' opinions and knowledge regarding novel and complex matters to inform strategic planning and policy design (Loo, 2002). Eliciting expert knowledge has been described as a useful method to inform outcome-oriented scaling initiatives (Wigboldus, 2016). Delphi studies seek agreement, dialectic disagreement, sharing insights, and a collective build-up of informed conclusions on complex issues (Vernon, 2009). Delphi surveys are structured communications among a panel of experts and are characterized by iteration, anonymity, and controlled feedback (Landeta & Barrutia, 2011). Despite conveying a statistical representation of expert panel responses, they fall within the realm of qualitative research methods (Barnes & Mattsson, 2016). Furthermore, Delphi surveys are usually combined with semi-structured and in-depth expert interviews (Beiderbeck et al., 2021; Schmalz et al., 2021).

Expert selection and panel composition

We selected the panelists based on purposive expert sampling (Gbededo & Liyanage, 2020). We relied on the knowledge and expertise of the experts (van Audenhove & Donders, 2019). Two eligibility criteria for participation were considered: participants were required (1) to have knowledge of two-dimensional materials and their application in energy storage technologies, and (2) to belong to specific stakeholder groups based on the context of our study. Accordingly, three stakeholder groups were of interest to our study: graphene producers/suppliers, EESDs developers/producers and users such as original equipment manufacturers, and researchers in academia and non-academic institutions. The identification of experts drew from publicly available information. This includes screening organizational documents, journal publications, and scientific conference records. Beyond screening these specialized documents, the identification of experts was further augmented through the researchers' network, who currently work within umbrella organizations.

The Delphi survey panel consisted of 25 leading international experts with an average experience of nearly twelve years, ranging from six to 35 years. This panel size is within the recommended range for Delphi studies (Okoli & Pawlowski, 2004). For more details on the composition of the Delphi survey panel, see Table 2. Before the Delphi survey, we conducted personal interviews with the experts. We first carried out 23 interviews, which were then completed by additional two interviews to cross-validate our interpretation of the Delphi survey results. In total, we carried out 25 interviews, which is substantially beyond the required size for initial interviews in Delphi studies (Beiderbeck et al., 2021). Sixteen of the 25 interviewees were also panelists in the Delphi survey. For more details on the interviewees' profiles, see Appendix A.

We carried out the Delphi survey in two rounds. In the second round, six out of 25 panelists dropped. However, we considered the assessments of the six panelists that did not respond during the second round as definitive. Accordingly, we included these in the analysis of the second round, which is considered a reasonable practice in Delphi studies (Landeta et al., 2011).

Data collection

First, we reviewed the factors influencing the mainstreaming of GRMs in EESDs. Based on this review, we designed our analytical framework, from which we determined a set of questions that guided us during the interviews. Following the interviews, we revisited our analytical framework to fine-tune it further. We then used the analytical framework and the insights from the interviews to design the Delphi survey.

The data were collected from March 2021 to February 2022, a typical timeframe for Delphi studies (Chand et al., 2020). We carried out 25 in-depth interviews that lasted an hour on average, ranging from 45 min to two hours. Despite approaching the interviews with a pre-defined set of questions, we also aimed at an in-depth understanding of specific topics. Therefore, the interviews were conducted using a semi-structured in-depth format. The objectives of the interviews were to frame the Delphi questionnaire, refine the analytical framework, find other informants, and contextualize the results of the Delphi survey.

The interviews were conducted in two distinct stages. In the first stage, we conducted 23 interviews that played an essential role in shaping the Delphi questionnaire and provided valuable qualitative insights. The last three of these interviews were used to pilot the Delphi questionnaire. Further, we invited interviewees to participate in the subsequent Delphi survey at the end of each interview and asked them to recommend additional interview participants. In the second stage, after the two rounds of the Delphi survey were completed, we

Table 2
Distribution of Delphi panelists by years of experience, country, and stakeholder group.

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

conducted two extra interviews to triangulate the interpretation of the results.

Following the first stage of expert interviews, we administered the Delphi survey in two separate rounds using an online platform. The Delphi questionnaire consisted of four questions with several sub-items based on a 5-point scale (from 1- low priority to 5- high priority) and captured the stakeholder group, years of experience, and country. We asked the panelists to evaluate how they believed the seventeen drivers and barriers to mainstreaming GRMs were currently prioritized and, in contrast, how they should be prioritized according to them. Given the multidisciplinary nature of the study, we intentionally chose not to require an answer to all seventeen items. We instructed the panelists that "no answer" was equivalent to not being familiar. Finally, the Delphi survey included open fields asking the panelists to provide comments where necessary.

After receiving the responses from the first round, we conducted an interim analysis that calculated the mean scores of each participant's assessments. The results of the interim analysis were distributed to all panelists via e-mail. In this individual communication with the experts, we included a table containing the mean scores of all items in one column and the personal scores of each panelist in another. This personal column highlighted the responses that varied strongly from the mean. We asked the panelists whether they disagreed or agreed with the general views expressed in averages and asked them to express their choices by filling out the same questionnaire again in its entirety or the specific scores highlighted in yellow. Responses for the second round were finally received via the online platform.

Analysis

The Delphi survey results were analyzed using descriptive statistics, focusing mainly on the averages to measure the panelists' assessments. In addition, we used standard deviation (SD) as a measure of consensus. For Delphi surveys on 10-point scale questions, an SD ≤ 2 is considered an appropriate consensus (von der Gracht, 2012). In this study, we used questions on a 5-point scale and considered an SD ≤ 1 as an adequate consensus.

Panelists rated the priority levels they believed were currently assigned and the priority levels they believed should be assigned. We constructed a thematic indicator (T_i) of prioritization sufficiency based on the difference between these two indicators. For this indicator, we relied on the initial consensus of the actual and required priority levels. In the case of dissensus, we relied on takeaways from the interviews to unpack the dissensus observed. The thematic indicator is based on an "if-then" rule type, and its functions are:

i. If $(T_i) > 0$ then prioritization is insufficient (Tension for acceleration)
ii. If $(T_i) < 0$ then prioritization is sufficient (Opportunity for acceleration)
iii. If $(T_i) = 0$ then prioritization is optimal

Then, following the approach of Salazar-Elena et al. (2020), we constructed a synthetic indicator (S_i) by normalizing the values of functions i. and ii. separately. The objective of this normalization is to flip the interpretation of the thematic indicator in case of insufficiency to action required for acceleration and in case of sufficient to opportunity for acceleration. We normalized the (S_i) using a widely used unity-based normalization formula to construct such indicators (Akanbi et al., 2015, p. 52; Freudenberg, 2003, p. 10), provided in Appendix B. This formula normalizes the values based on the distance from the worst-performing value. Accordingly, the normalized value of the worst performer becomes 0, and that of the best performer becomes 1. This normalization of values provides a consistent and comparable interpretation across all items.

The normalized values for insufficiency are referred to as "urgency to act" and for sufficiency as "opportunity to accelerate." The closer (S_i) is to zero, the smaller its impact is perceived to be, and the further it tends toward 1, the greater its impact becomes. However, for the normalized values, we focus on values ≥0.2 and ≤ 0.8. The underlying principle for this range is that we assume that the drivers and barriers are virtually impossible to be optimally prioritized due to the subjective reality we live in. Therefore, we assume that values of the normalized scores <0.2 to be semi-optimally prioritized and > 0.8 to experience limited to no change in the short term. On the contrary, values >8 may still be impactful but are considered unlikely to produce a meaningful change in the short- and intermediate-term.

Results

The analysis in this section is divided into two main sections. First, Tables 3 and 4 present the results of the Delphi survey, which are further analyzed on a disaggregate level. Second, Figs. 1, 2, and 3 illustrate the results of the Delphi survey to analyze the categories of the drivers and barriers on an aggregate level to detect similarities and differences among them.

Adaptive priority-setting of drivers

Table 3 presents the mean assessments of how the panelists believed the drivers to mainstreaming GRMs were currently prioritized and how they should be prioritized.

Table 3
Required vs. current prioritization of the drivers to mainstreaming GRMs in EESDs.

1- Low priority to 5 – high priority			Round 1		Round 2	
			Mean	SD	Mean	SD
Internal drivers	Improve energy density	Desirable	3.5	0.92	3.7	0.8
		Actual	2.8	0.99	2.8	0.8
		Insufficient	0.7		0.8	
		Urgency for action	0.4		0	
	Improve power density	Desirable	3.9	0.68	4	0.66
		Actual	3.2	0.92	3.2	0.82
		Insufficient	0.7		0.8	
		Urgency for action	0.4		0	
	Improve life cycle	Desirable	3	1.3	3.5	0.98
		Actual	2.3	0.96	2.2	0.64
		Insufficient	0.7		1.3	
		Urgency for action	0.4		0.6	
	Improve safety	Desirable	2.5	1.14	2.8	0.93
		Actual	2.2	1.01	1.8	0.56
		Insufficient	0.3		1	
		Urgency for action	0		0.2	
External drivers	Reduce overall costs	Desirable	2.8	1.41	3.3	1.17
		Actual	2	1.08	2	0.93
		Insufficient	0.8		1.2	
		Urgency for action	0.5		0.5	
	Reduce waste	Desirable	2.8	1.25	3.3	0.94
		Actual	2.2	1.2	2.1	0.97
		Insufficient	0.6		1.2	
		Urgency for action	0.3		0.4	
	Substitute critical materials	Desirable	2.9	1.55	3.6	1.22
		Actual	2	1.22	2	0.96
		Insufficient	0.9		1.6	
		Urgency for action	0.6		1	
	Overcome socio-political challenges	Desirable	2.8	1.35	3.2	1.04
		Actual	2.2	1.21	2	0.82
		Insufficient	0.6		1.2	
		Urgency for action	0.3		0.5	
	Spur competition with non-sustainable applications	Desirable	3.3	1.34	3.9	0.97
		Actual	2.6	1.33	2.4	0.96
		Insufficient	0.7		1.4	
		Urgency for action	0.4		0.8	

Table 4
Required vs. current prioritization of the barriers to mainstreaming GRMs in EESDs.

1- Low priority to 5 – high priority			Round 1		Round 2	
			Mean	SD	Mean	SD
Technological limitations	Improve quality	Desirable	3.7	0.89	4.0	0.61
		Actual	3.2	1.14	3.2	0.85
		Insufficient	0.6		0.9	
		Urgency for action	0.2		0.1	
	Improve scalability	Desirable	4.0	1.10	4.3	0.85
		Actual	3.3	1.31	3.1	0.95
		Insufficient	0.8		1.2	
		Urgency for action	0.5		0.5	
	Improve processability	Desirable	3.9	1.04	4.2	0.85
		Actual	3.1	1.20	3.1	0.95
		Insufficient	0.5		1.1	
		Urgency for action	0.5		0.3	
	Improve/lower prices of graphene materials	Desirable	4.3	0.90	4.4	0.91
		Actual	3.2	1.25	2.9	0.97
		Insufficient	1.2		1.5	
		Urgency for action	0.9		0.9	
Reconfiguration barriers	Aligning handling practices	Desirable	3.8	0.92	4.0	0.72
		Actual	2.5	1.10	2.4	0.91
		Insufficient	1.3		1.5	
		Urgency for action	1.0		0.9	
	Aligning equipment configuration	Desirable	3.0	1.21	3.4	1.10
		Actual	2.5	1.18	2.3	0.83
		Insufficient	0.6		1.1	
		Urgency for action	0.3		0.4	
	Aligning storage practices	Desirable	3.2	1.26	3.7	0.95
		Actual	2.5	1.19	2.4	0.90
		Insufficient	0.7		1.3	
		Urgency for action	0.4		0.6	
	Aligning transport practices	Desirable	3.0	1.35	3.5	1.06
		Actual	2.2	1.15	2.2	0.80
		Insufficient	0.8		1.4	
		Urgency for action	0.5		0.7	

According to the current priority levels of the internal drivers, improving power density seems to be of great interest. The expert panel reached consensus on this assessment in both rounds. In the second, however, the consensus on the actual priority level for improving power density was even more robust (SD 0.82). This is followed by the driver of improving energy density, which is slightly above average, as indicated by the score of (2.8) as a mean assessment for both rounds. The panelists reached consensus on this priority level for both rounds.

In the same line of current priority levels, the panelists perceived life cycle improvement and safety to be prioritized as below average. Regarding life cycle improvement, the change in the mean assessment between the first and second rounds was relatively small. However, the consensus level dropped significantly from (0.96) to (0.64), indicating a solid consensus on how life cycle improvement is currently prioritized. For safety improvement, the mean score decreased from (2.2) in the first round to (1.8) in the second round. Panelists diverged in the first round (SD 1.01) but reached solid consensus in the second round (SD 0.56).

In terms of the actual priority levels of the external drivers, spurring competition with unsustainable applications appears to be the highest priority. Panelists viewed this driver as currently prioritized average, i.e., (2.6) in the first round and (2.4) in the second round. In the first round, the panel diverged on the current priority level (SD 1.33). In the second round, however, the panel reached a reasonable consensus on this "average" prioritization (SD 0.96). The second top priority is the driver of reducing waste, with a mean assessment of (2.1) in the second round, which is "below average." The other influencing factors were rated relatively similar to the second highest priority. However, there is a striking similarity between the first and second rounds for the external drivers, which is the fact that in the second round, the panel reached consensus on the actual priority levels of these drivers being currently prioritized as "below average."

In contrast, from the required priority level's perspective, experts perceived the current priority levels to mismatch the required priority levels for all the drivers. Starting from the internal drivers, with strong consensus (SD 0.66), the panelists perceived that improving power density should be prioritized as the highest. The panelists' assessments remained relatively similar between the two rounds regarding the improvement of power density. The second top required priority is improving energy density, on which the experts also reached a strong consensus (SD 0.8) with a slight change in the mean assessment between the two rounds. The third top priority is the improvement in life cycle. In the first round, the panelists diverged on the required priority levels. However, in the second round, the panelists reached a consensus (SD 0.98). The change between the two rounds in the mean assessment went from being "slightly above average" to "substantially above average" or even "nearly high priority." Finally, the lowest required priority within the internal drivers is improving safety. Although panelists were far apart in the first round (SD 1.14), they reached a relatively strong consensus in the second round (SD 0.93).

At the same time, the panelists perceived the external drivers to be prioritized largely below the internal drivers, i.e., for both the current and required priority levels. In terms of current priority levels, the top priority for external drivers is making GRMs-enhanced EESDs competitive relative to unsustainable applications. Panelists rated spurring competition with unsustainable applications as "semi average," with a slight change between the first and second rounds. Experts reached a relatively strong consensus on this assessment in the second round (SD 0.96). The remaining four drivers are perceived to be currently prioritized as relatively similar and "below average." In the first round, panelists diverged widely on the current priority levels of the external drivers, but in the second round, they reached a reasonably strong consensus.

On the other hand, panelists seem to have different views on the required priority levels of the external drivers. In particular, the experts viewed spurring competition with unsustainable applications as the top priority, with an assessment being relatively high in the second round after being "above average" in the first round. Despite the panelists diverging on the required priority for this driver in the first round, they reached consensus in the second round. Further, substituting critical materials was the second top priority for both rounds. However, the experts diverged widely on the required priority levels for both rounds regarding the driver of substituting critical materials. In addition, the panelists perceived the remaining three drivers as quite similar in the first and second rounds. However, the assessment increased from slightly above average in the first round to substantially above average in the second round. Also, the experts diverged extensively on the required priority levels in both rounds, apart from reaching consensus in the second round on the driver of reducing waste (SD 0.94).

Considering the thematic indicator of prioritization sufficiency, we observe a pattern of prioritization insufficiency across both categories of drivers. The highest prioritization insufficiencies are observed for the external drivers. In particular, the driver of substituting critical materials seems to be the top insufficiency. The panel diverged widely on the required priority in the first and second rounds. The second top insufficiency is observed for making GRMs-enhanced EESDs competitive relative to unsustainable applications. This insufficiency increased in the second round due to changes in the experts' assessments of the actual and required priority levels. In the second round, the panel reached a relatively strong consensus on both the required and actual priority levels, hence giving more weight to the insufficiency of this driver. The third top insufficiency is simultaneously observed for the drivers of overcoming socio-political challenges, reducing waste, and reducing overall costs. For reducing waste, the panel reached consensus in the second round on the required and actual priority levels. Whereas for overcoming socio-political challenges, the panel diverged on the required priority levels in the first and second rounds. While reducing overall costs, the panel diverged on the required priority levels in the second round.

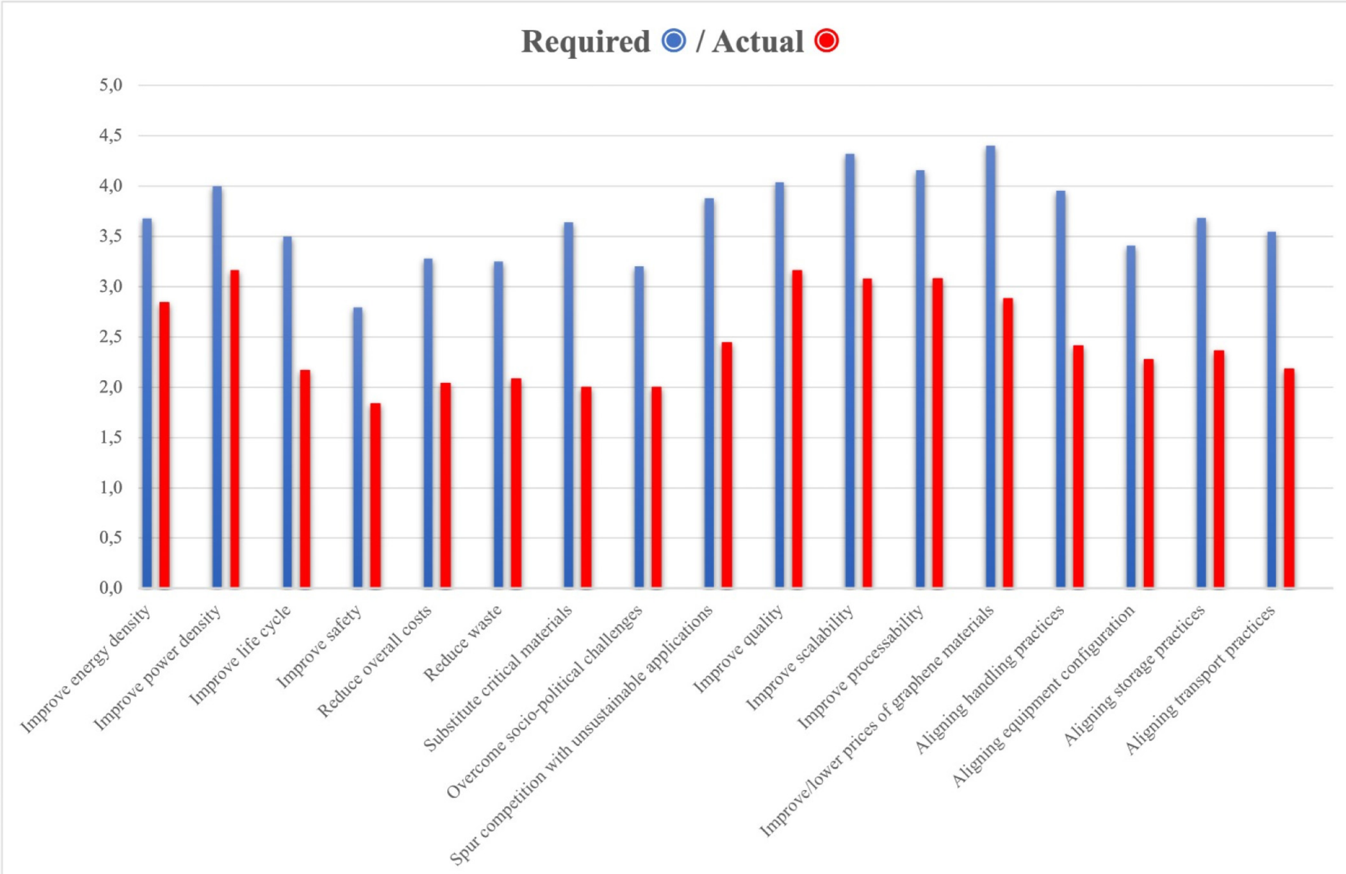

Fig. 1. Patterns of required and actual prioritization trajectories.

On the dissensus observed above, some of the experts voiced different views. One expert commented: "The question is not whether graphene can or cannot be a potential solution, it is more about will it really be a realistic solution? I think yes, but we have a long way to reach to this point." Another expert said: "Usually these drivers [external drivers] are far in the future and too radical, making them desirable for some and less so for others. And when you are developing a technology, you focus on immediate and tangible outcomes." Another expert added, "This may be because of the benefits of the current materials compared to graphene (and here we are not talking about theoretical potential, just current situation) either with regard to the performance or economic benefits, which could lead actors not to desire such a change."

Moreover, the insufficiency of the internal drivers is lower than that of external drivers. The top insufficiency lies in the driver of improving life cycle of EESDs. In the second round, panelists agreed on the required and the actual priority. Then, the second top insufficiency is the improvement of safety on the panel also reached consensus for both the actual and required priority levels. Further, the lowest insufficiencies are observed simultaneously for improving energy and power densities, which also have strong consensuses on the actual and required priorities in the second round.

Due to these insufficiencies, several items fell within the established range of urgency for action to bend their prioritization trajectories in the right direction and accelerate mainstreaming GRMs in EESDs. The top urgency for action is observed for improving life cycle (S_i 0.6). Then, the experts perceived the reduction of overall costs and overcoming socio-political challenges to be the second top drivers "simultaneously" to require urgency for action (S_i 0.5). However, experts diverged on the required priority levels for both drivers in the second round. Further, the panelists perceived the third top urgency for action as the driver of reducing waste (S_i 0.4). As for the drivers of improving power and energy density, the urgency for action is <0.2; hence, they are perceived not to require urgency for action. On the other hand, the urgency for action for the drivers of safety and substituting critical materials is >0.8; therefore, these drivers are perceived to have limited or no impact in the near future as the urgency for action is significant and unlikely to produce discernible impact.

Adaptive priority-setting of barriers

Table 4 presents the mean assessments of how the panelists believed the barriers to mainstreaming GRMs were currently prioritized and how they should be prioritized.

According to the current prioritization trajectories, the panel considered the quality barrier as the main concern. In the first round, panelists' opinions differed on the actual prioritization of quality (SD 1.14), but in the second round, they reached a strong consensus (SD 0.85). After that, improving scalability and processability were perceived "equally" as the second highest priority. On both items, the panel diverged in the first round. However, in the second round, the panel reached a strong consensus (SD 0.95). Improving prices of GRMs ranked third with an "above average" prioritization (2.9). The panel reached consensus on this prioritization in the second round (SD 0.97). In the first round, the driver of improving prices was slightly higher (3.2), but the panel diverged widely on this prioritization (SD 1.25).

Regarding the reconfiguration barriers, experts viewed reconfiguring handling practices and aligning storage practices as the highest priority. In the first round, this prioritization was average, but the experts diverged widely. In the second round, however, the panel

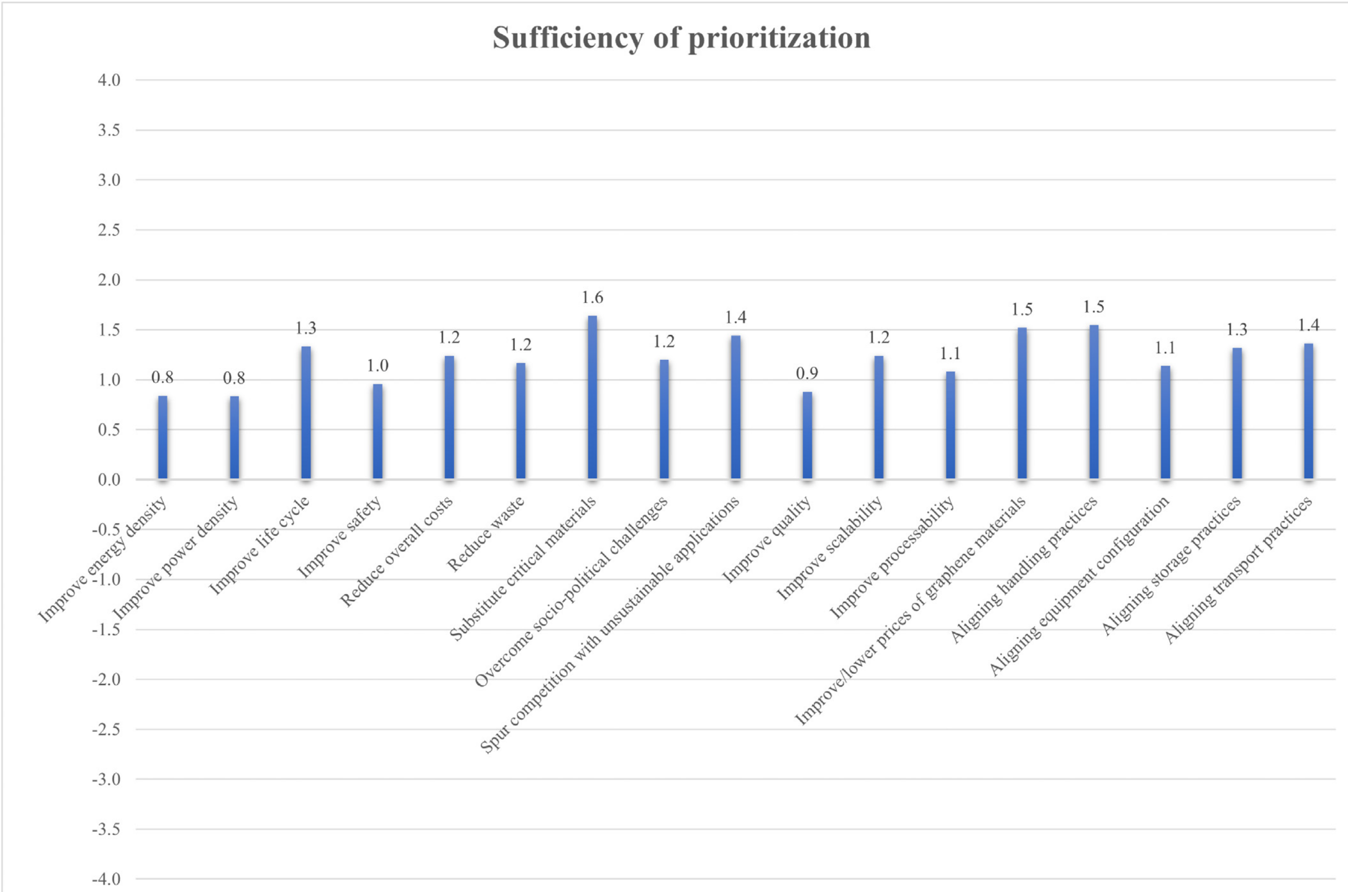

Fig. 2. Patterns of sufficiency indicator.

reached a reasonable consensus. Reconfiguring equipment arrangements was viewed as the second highest priority, with an average rating (2.3) in the second round and a slight deviation compared to the first round (2.5). The panel diverged widely in the first round (SD 1.18), but in the second round a solid consensus was reached (SD 0.83). The panel perceived reconfiguring transportation practices to be prioritized below average (2.2). In the first round, this rating was similar, but the panel diverged (SD 1.15). In the second round, however, the panel reached a strong consensus.

On the other hand, the panelists had different views on how the barriers should be prioritized. Starting from the top priority, the panel felt that the driver of improving the prices of GRMs should be prioritized substantially high (4.4). Most importantly, the panel reached solid consensus in both rounds on how the prices of GRMs should be prioritized. Then, improving scalability was perceived as the second top priority (4.3), on which the panel reached consensus in the second round (SD 0.85). Further, improving processability came as the third top priority (4.2). In the first round, there was a weak divergence among the panelists on this item (SD 1.04), but in the second round, they reached strong consensus (0.85). After that, the panel perceived that the driver of improving quality and reconfiguring handling practices should be prioritized similarly (4.0). The panel reached strong consensuses in both rounds (SD 0.61 and 0.72, respectively). This is followed by reconfiguring storage practices (3.7), on which the panel reached consensus (SD 0.95). Nevertheless, in the first round, the panelists diverged extensively on how reconfiguring storage practices should be prioritized (1.26).

Moreover, the panel perceived reconfiguring transport practices and equipment reconfigurations to be prioritized as slightly similar (3.5 and 3.4, respectively). These priority levels are relatively high and have changed substantially compared to the first round. In the first round, the panel diverged significantly (SD 1.35 and 1.21, respectively). In the second round, they converged slightly more than in the first round but still did not reach consensus on how these items should be prioritized (SD 1.06 and 1.10, respectively).

Illustrating the prioritization sufficiency, the panelists perceived the driver of reconfiguring handling practices to be considerably insufficiently prioritized. The experts agreed extensively on this insufficiency, with relatively strong consensus in both rounds. An expert commented: "In some very specific cases, you need specialized expertise, and sometimes even in the setup of the devices and technologies, you require consultancy that is unfortunately not always available, and in this case, I don't expect it to be available everywhere to enable such scaling initiative." Another expert added: "Companies that produce batteries already have in-house experts and researchers, but they may not be able to replicate everything done in labs at large scales because at large scale, you need to control many more things and I don't expect them to have all the required knowledge to deal with everything."

Then, reconfiguring transport and storage practices are perceived to be the second highest insufficiency within the barriers. However, the panelists diverged widely on how these items should be prioritized compared to how they are currently prioritized. Within the reconfiguration barriers reconfiguring equipment configuration is also insufficiently prioritized. But there is overwhelming dissensus among the experts on how this item should be prioritized. One expert referenced (Arvidsson et al., 2018), arguing: "Graphene shouldn't be dealt with as if it were a completely new material; it is just carbon." Similarly, another expert stated that "There is nothing disruptive, it will have to fit existing

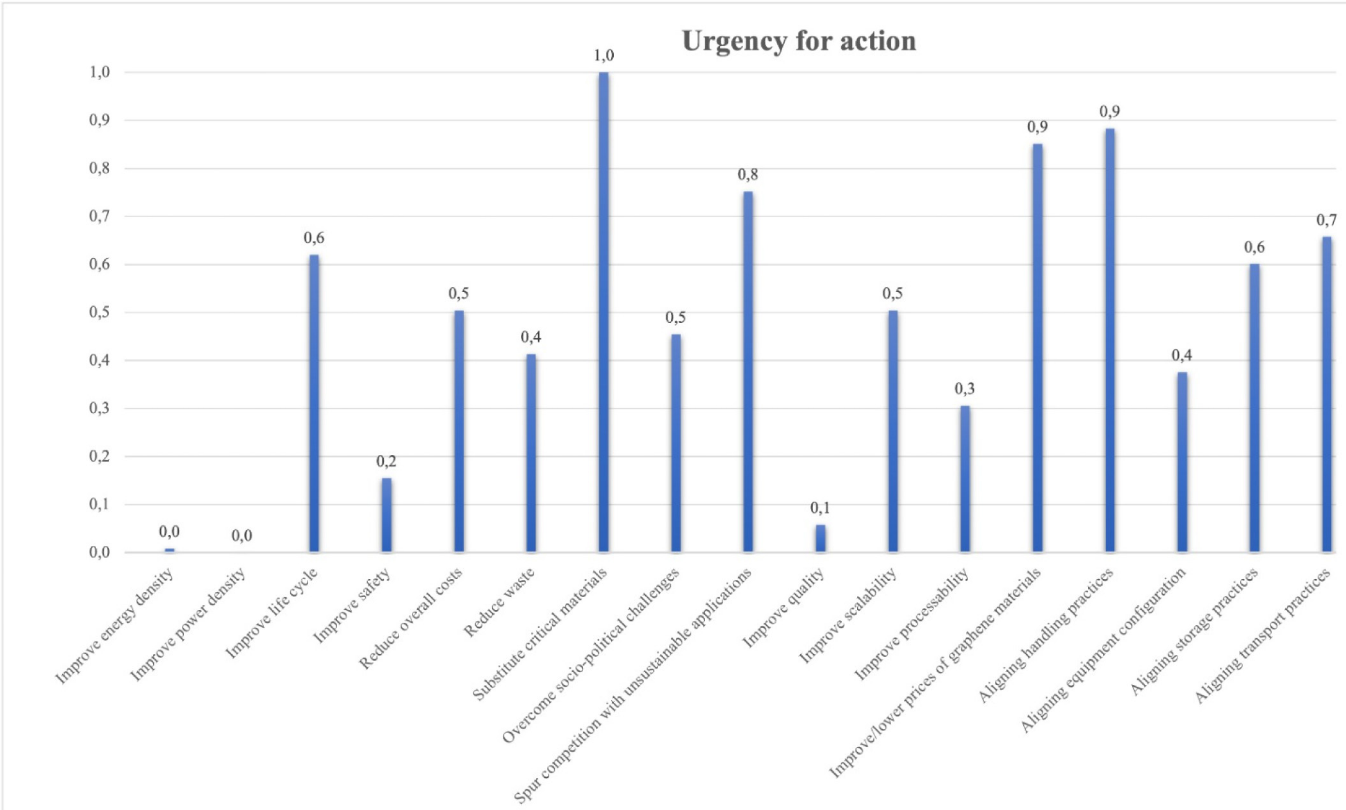

Fig. 3. Patterns of urgency for action.

configurations." Still, it is worth mentioning that the concept of reconfiguration was a new topic to many of the panelists. An expert added: "For materials producers, these are not a barrier, but for the companies working with these materials it is [a barrier], which I believe does affect their decision to adopt new materials." Thus, it is reasonable to assume that the disagreement may have resulted from the different views between producers and users.

Furthermore, the technological limitations are also significantly insufficiently prioritized. For example, the highest insufficiency is observed for improving GRMs prices. The panelists agreed extensively on this insufficiency, i.e., according to the consensus on the required and actual priority levels. Remarkably, this insufficiency is the highest among all the barriers. One expert explained this insufficiency stating, "Mostly, we look at reference materials (e.g., graphite), which are significantly cheaper than GRMs. But one would expect such higher prices because of the added value of GRMs. But even with such an added value, current prices seem to be very high." From a slightly different perspective, another expert commented, "I expect graphene prices to drop as demand increases. There is this factor of economies of scale that we haven't reached yet, which could play a role in decreasing prices of GRMs."

Then, the insufficiency for improving scalability is also high, and in the second round, this insufficiency became more robust due to the overwhelming consensus on the required and actual priority levels. Further, the experts perceived improving processability to be broadly insufficiently prioritized, which is also agreed upon extensively. The lowest insufficiency is observed for improving quality. Improving quality seems to be insufficiently prioritized with an overwhelming consensus.

Due to this insufficient prioritization, several barriers are perceived to demand urgent action to bend their prioritization trajectories in the right direction. Accordingly, many barriers fell within the established range of urgency. Within the technological limitations, scalability is the top item requiring urgent action (S_i 0.5). Processability also is perceived to require urgent action (S_i 0.3). The panel agreed on both items' required and actual prioritization. Regarding the reconfiguration barriers, reconfiguring storage practices is perceived to require urgent action (S_i 0.6). The panel agreed on this driver's required and action priority levels; therefore, there is a solid urgency for action. Then, reconfiguring transport practices is perceived to have a relatively high urgency for action (S_i 0.7). However, the panel reached weak dissensus on the required priority level on how this driver should be prioritized. Similarly, reconfiguring equipment arrangements also required urgent action (S_i 0.4). But the panel disagreed on the required priority levels. Apart from that, the urgency for action to improve quality appears to be relatively low. On the contrary, improving prices and reconfiguring handling practices seem to have an urgency for action of (S_i 0.9), and hence this urgency for action is unlikely to produce meaningful progress in the near future.

Aggregate analysis

Figs. 1, 2, and 3 illustrate the results of the Delphi survey presented in Tables 3 and 4. These Figures are presented to analyze the similarities and differences among the drivers and barriers on an aggregate level.

As illustrated in Fig. 1, technological limitations are generally perceived as top priorities from the perspective of both the actual and the required priority levels. Most of the internal drivers also match the required priority levels of the technological limitations on a disaggregate level. This is particularly evident for the required priority levels. In contrast, only some internal drivers match the actual priority levels. However, the technological limitations and the internal drivers appear to be the top priorities, both from actual and required priority levels, with the technological limitations being the overriding priorities.

Although within the internal drivers, at least, the driver of safety is perceived to be inadequately prioritized.

On the other hand, the panel perceived the external drivers and the reconfiguration barriers as currently prioritized below average. The external drivers are currently prioritized as the lowest among all the other categories of drivers and barriers. However, there is a striking similarity between the external drivers and the reconfiguration barriers: they are perceived to require relatively the same priority levels. However, the reconfiguration barriers are ranked slightly above the external drivers from the actual priority levels.

As illustrated in Fig. 2, all drivers and barriers are perceived to be insufficiently prioritized. The insufficient prioritization of all the determinants represents a remarkable similarity among all the drivers and barriers. In contrast, the panel perceived none of the determinants to correspond to an opportunity to accelerate mainstreaming, which is a notable similarity across categories. On the aggregate level, there is a slight similarity in insufficiency between the internal drivers and the technological limitations. However, the barrier of GRMs prices is perceived to be significantly insufficiently prioritized.

On the other hand, there appears to be a slight similarity between the external drivers and the reconfiguration barriers, which differ in terms of insufficiency from the internal drivers and technological limitations. The panel viewed the insufficiency of the external drivers and the reconfiguration barriers to be much higher than the internal drivers and the technological barriers.

On the flip side of the tensions created by the insufficiency of prioritization, the panel perceived that many drivers and barriers require urgent action to bend the prioritization trajectories in the right direction. In Fig. 3. the drivers and barriers that fall within the range of 0.2 and 0.8 are the ones that require urgent action. On an aggregate level, many differences can be observed. For example, experts saw the external drivers to require the highest urgency for action. Reconfiguration barriers are reasonably close in terms of urgent action required but still fall below the external drivers. Notably, the internal drivers seem to be nearly optimally prioritized, except for improving the life cycle. Furthermore, there are a few drivers and barriers that are perceived to require an urgency for action >0.8, but they are dispersed with no similarities on an aggregate level can be observed.

Discussion

In this study, we have developed a novel approach of "adaptive priority-setting" to explore how the prioritization of interdependent drivers and barriers shapes accelerating the mainstreaming of GRMs in EESDs. We departed from the idea that orchestrating a pull scaling to accelerate mainstreaming requires setting multiple interdependent drivers and barriers as a vision and prioritizing them sufficiently to stimulate enabling conditions to achieve the intended outcomes.

Overall, our analysis reveals that the interdependent drivers and barriers to mainstreaming GRMs in EESDs are ill-prioritized. They influence the creation of a conducive environment for pull scaling and moderate the acceleration of mainstreaming. Specifically, the prioritization trajectories shape accelerating the mainstreaming on three levels. First, the drivers and barriers are prioritized inadequately, i.e., not being set simultaneously as a vision to stimulate enabling conditions for mainstreaming. Second, the drivers and barriers are creating tensions for mainstreaming GRMs, and accelerating the mainstreaming requires urgent action to bend the prioritization trajectories in the right direction. Third, our analysis of the prioritization dynamics suggests a strong focus on the internal drivers and technological limitations over the external drivers and the reconfiguration barriers.

The drivers and barriers are not coherently forming a vision to orchestrate pull scaling and self-organized mainstreaming. We find this to be an issue on a disaggregate and aggregate level. For example, the key internal drivers that are considered prime priorities are the drivers of improving energy and power density. We find widespread consensus that the use of GRMs in EESDs will be predominantly centered around these two drivers. Also, we find the external drivers to be disproportionately prioritized. This suggests that the different drivers are being used as a "vehicle" to create expectations and diffuse GRMs to make the drivers of improving power and energy densities materialize. Accordingly, in the near future, we expect the application of GRMs in EESDs to be predominantly known as a material enabling higher energy and power densities in EESDs. In some rare applications, GRMs may be used to improve safety and life cycle of EESDs. However, the overall pattern shows it is likely to be mainly used as a material for improving energy and power densities.

While regarding the barriers, we find the technological limitations to be the maximum priority. On a disaggregate level, we find that the quality of GRMs will likely improve significantly in the near future. While quality is likely to improve, we find the rest of the barriers to continue hampering the mainstreaming of GRMs. Key issues are the prices and scalability of GRMs, which we find very improbable to improve in the short- and intermediate-term future. This may imply that GRMs will likely be positioned as new materials with superior added value and premium prices that will continue to be available in relatively niche applications. However, in such circumstances, incumbent technologies may still not be replaced, and the co-existence of both technologies may imply a continuation of unsustainable modes of production and consumption.

In terms of reconfiguration barriers, we find the reconfiguration barriers unlikely to reconfigure in the short- and intermediate-term. On a disaggregate level, a key influencing factor in mainstreaming GRMs is reconfiguring handling practices. Factors like handling practices are convoluted and may affect the mainstreaming of GRMs due to their spatial availability (Huang et al., 2018, 2021). The inaccessibility to specialized knowledge and lack of reconfigurations of incumbent arrangements are thus key factors to continue influencing the mainstreaming of GRMs in EESDs. This implies that there will be technology leaders (primarily core countries) and technology followers or adopters (primarily periphery countries) (Castrejon-Campos, 2022). In this context, sustainability challenges such as decarbonization and climate change are likely to persist and take longer to address.

On a slightly more aggregated level, the drivers and barriers appear to constitute tensions for mainstreaming GRMs. We find widespread consensus that the drivers and barriers are perceived to be insufficiently prioritized. In the context of non-coordinated ecosystems, optimal prioritization may be subjective and impossible to achieve, as such ecosystems initially may not allow for strategic orientation (Larrue, 2021). However, we find the drivers and barriers to be insufficiently prioritized significantly. We observe the perceived insufficiency to be exceptionally high for external drivers and the reconfiguration barriers along with improving prices of GRMs and improving the life cycle of EESDs. The external drivers and reconfiguration barriers are perceived as insufficiently prioritized and may be driven by vested interests of different actors in incumbent technologies, which may resist reconfiguration. At the same time, such vested interests directly affect the extent to which the external drivers are insufficiently prioritized. Such prioritization trajectories mean that mainstreaming GRMs in EESDs would require the emergence of new actors, i.e., new actors entering with niche innovations.

On a fully aggerate level, the current priorities give technological drivers and barriers an advantage over external drivers and reconfiguration barriers. Despite the interdependency among the drivers and barriers, the external drivers and the reconfiguration barriers are inadequately prioritized. An important reason for not adequately prioritizing the reconfiguration barriers may be the commonly held perception that GRMs may be yet another carbon material and therefore do not require reconfiguring incumbent arrangements. On the other hand, a possible explanation for not adequately prioritizing the sustainability pressures may be because sustainability is a public good and private actors may have limited interest in addressing such drivers.

Our study finds the external drivers to be a highly disputed topic among the expert panel. On the one hand, according to relatively small-scale experiments, it is claimed that the scaling of GRMs would likely address such drivers. While technological feasibility may be achieved at such a small scale, there is widespread consensus that the mainstreaming GRMs niche applications to address the external drivers seems to be far in the future. Therefore, it may be unlikely to address such drivers in the short- and intermediate-term.

Nevertheless, tensions can also be reframed as an opportunity to shift the prioritization trajectories in the right direction and create favorable conditions for pull scaling. Creating such a favorable environment for pull scaling, in the short and medium term, requires drastic policies as most drivers and barriers require urgent action. Only a few drivers and barriers were "nearly optimally prioritized," and others were exceedingly insufficiently prioritized, requiring no urgent action. But the vast majority of the drivers and barriers were perceived to require urgent action, specifically the external drivers and reconfiguration barriers. Not surprisingly, the external drivers and the reconfiguration barriers require higher urgency for action than the technological drivers and barriers since they are perceived to be a top concern. But what is of prime concern for accelerating the mainstreaming of GRMs is the creation of a conducive environment for pull scaling, which requires setting the drivers and barriers as a vision with adequate and sufficient priority levels.

However, bending the trajectories in the right direction is challenging, given that the GRMs ecosystem is relatively non-coordinated, with the exemption of some regional projects. Therefore, the call for urgent action to bend the prioritization trajectories in the right direction is directed not only by GRMs and EESDs producers but also by policymakers, as they play a crucial role in mainstreaming initiatives (Wigboldus, 2016; Wigboldus et al., 2016). On the one hand, GRMs and EESDs producers need to address the articulation of societal needs beyond technological progress and application developments. This is highlighted by the urgency for action, specifically regarding the external drivers. On the other hand, policymakers need to: a) foster more profound collaboration between EESDs developers and GRMs producers to create enabling conditions and b) devise essential policies regarding the use and import of critical materials.

Conclusion

Despite the significant potential that GRMs hold to transform current and future-generation EESDs, their mainstreaming to address societal problems is complex. The current prioritization trajectories of drivers and barriers to mainstreaming GRMs in EESDs fall short in creating a conducive environment for pull scaling. They "under-privilege" reconfiguration barriers and major sustainability pressures. In addition, the prioritization of interdependent drivers and barriers is widely perceived to constitute tensions for mainstreaming. Expectations among key stakeholders are low regarding the current prioritization trajectories to mainstream GRMs in EESDs. Drivers and barriers should be prioritized sufficiently and adequately to accelerate the mainstreaming of GRMs and help address societal problems and decarbonization of the transportation sectors.

In conclusion, our study suggests that GRMs currently remain somewhat a niche technology in EESDs within a stable status quo based on incumbent technologies and rigid configurations. Accordingly, mainstreaming GRMs is likely to rely on the value of the technology and follow the dynamics of push scaling, where a relatively stable incumbent regime is challenged, disrupted, and competed with. However, this is likely to result in inefficiencies and may fail to achieve impact at scale. Against this backdrop, mainstreaming GRMs is, thus, likely to take longer unless significant and collective action is taken to shift current prioritization trajectories in the right direction and create an enabling environment for pull scaling. This is because the ongoing prioritization can do little to address the electrification of the transportation sector and help achieve decarbonization goals, which are woefully adrift of viable solutions. Although GRMs have the potential to transform these challenges, the current prioritization trajectories fail to enable such a transformation, and therefore, urgent action is needed.

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.

Acknowledgements

We would like to thank Dr. Franziska C. Löhrer and Muhamad Alif Bin Ibrahim for their unwavering help. Also, we would like to thank all experts that participated in this study and made it possible.

Funding

The first author received funding from the Economic Development Agency for La Rioja, under the doctoral fellowship program, grant number: 1168/2018 (*Resolución de concesión nº 1168/2018, de la Consejera de Desarrollo Económico e Innovación*).

Appendix A. 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	A large original equipment manufacturer	Germany	EESDs developer/user
4	Researcher	A large university-based center on graphene	United Kingdom	Researcher
5	Head of a department	A national institute focused on graphene	United Kingdom	Researcher
6	Researcher	A large original equipment manufacturer	Germany	EESDs developer/user
7	Researcher	A national institute focused on batteries cells	Germany	Researcher
8	Researcher	A national materials institute	Spain	Researcher
9	Program manager	A program manager in EU led initiative	Italy	Researcher
10	Product manager	A Medium-sized graphene supplier	Spain	Graphene producer
11	Innovator	A 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	A national center for renewable energies	Spain	EESDs developer/user
14	Researcher	A national research center for electrochemical and thermal energy storage	Spain	Researcher
15	Senior researcher	A state-owned research institute	Sweden	Researcher
16	Researcher	A research institute focused on developing graphene nanoparticles	Spain	Researcher
17	CEO	A medium-sized graphene producer/supplier	Spain	Graphene producer
18	Researcher	A large graphene producer	United Kingdom/Sweden	Graphene producer
19	Program manager	A large graphene producer	United Kingdom	Graphene producer
20	Researcher	A national institute focused on batteries cells	Germany	Researcher
21	Project manager	A medium-sized graphene producer/supplier	Spain	Graphene producer

(*continued*)

	Role/Position	Type of organization	Country	Stakeholder group
22	Researcher	A national research center for electrochemical and thermal energy storage	Spain	Researcher
23	Technology transfer	A medium-sized graphene supplier	Italy	Graphene producer
24	R&D	A large graphene producer	Spain	Graphene producer
25	Technology transfer	A medium-sized graphene producer/supplier	Italy	Graphene producer

Appendix B. Formula used to construct the synthetic indicator

$$S_i = \frac{X - X_{min}}{X_{max} - X_{min}}$$

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

References

Akanbi, O. A., Amiri, I. S., & Fazeldehkordi, E. (2015). A machine-learning approach to phishing detection and defense. *A machine-learning approach to phishing detection and defense*. Elsevier. https://doi.org/10.1016/C2014-0-03762-8.

Arkesteijn, M., van Mierlo, B., & Leeuwis, C. (2015). The need for reflexive evaluation approaches in development cooperation. *Evaluation*, *21*(1), 99–115. https://doi.org/10.1177/1356389014564719.

Arvidsson, R., Boholm, M., Johansson, M., & de Montoya, M. L. (2018). "Just Carbon": Ideas about graphene risks by graphene researchers and innovation advisors. *NanoEthics*, *12*(3), 199–210. https://doi.org/10.1007/s11569-018-0324-y.

Arvidsson, R., & Sandén, B. A. (2017). Carbon nanomaterials as potential substitutes for scarce metals. *Journal of Cleaner Production*, *156*, 253–261. https://doi.org/10.1016/j.jclepro.2017.04.048.

Ballinger, B., Stringer, M., Schmeda-Lopez, D. R., Kefford, B., Parkinson, B., Greig, C., & Smart, S. (2019). The vulnerability of electric vehicle deployment to critical mineral supply. *Applied Energy*, *255*(April), Article 113844. https://doi.org/10.1016/j.apenergy.2019.113844.

Barnes, S. J., & Mattsson, J. (2016). Understanding current and future issues in collaborative consumption: A four-stage Delphi study. *Technological Forecasting and Social Change*, *104*, 200–211. https://doi.org/10.1016/j.techfore.2016.01.006.

Behrens, S. H., Breedveld, V., Mujica, M., & Filler, M. A. (2017). Process principles for large-scale nanomanufacturing. *Annual Review of Chemical and Biomolecular Engineering*, *8* (1), 201–226. https://doi.org/10.1146/annurev-chembioeng-060816-101522.

Beiderbeck, D., Frevel, N., von der Gracht, H. A., Schmidt, S. L., & Schweitzer, V. M. (2021). Preparing, conducting, and analyzing Delphi surveys: Cross-disciplinary practices, new directions, and advancements. *MethodsX*, *8*, Article 101401. https://doi.org/10.1016/j.mex.2021.101401.

Biggi, G., & Giuliani, E. (2021). The noxious consequences of innovation: What do we know? *Industry and Innovation*, *28*(1), 19–41. https://doi.org/10.1080/13662716.2020.1726729.

Bøggild, P. (2018). The war on fake graphene. *Nature*, *562*(7728), 502–503. https://doi.org/10.1038/d41586-018-06939-4.

Boulanger, N., Skrypnychuk, V., Nordenström, A., Moreno-Fernández, G., Granados-Moreno, M., Carriazo, D., Mysyk, R., Bracciale, G., Bondavalli, P., & Talyzin, A. V. (2021). Spray deposition of supercapacitor electrodes using environmentally friendly aqueous activated graphene and activated carbon dispersions for industrial implementation. *ChemElectroChem*, *8*(7), 1349–1361. https://doi.org/10.1002/celc.202100235.

Braun, G., & Skinner, D. (2007). Experience scaling-up manufacturing of emerging photovoltaic technologies. Contract, January. http://lib.semi.ac.cn:8080/tsh/dzzy/wsqk/guofangkeji/Experience-scaling-up-manufacturing-of-emerging-photovoltaic-technologies.pdf.

Burd, J. T. J., Moore, E. A., Ezzat, H., Kirchain, R., & Roth, R. (2021). Improvements in electric vehicle battery technology influence vehicle lightweighting and material substitution decisions. *Applied Energy*, *283*(November), Article 116269. https://doi.org/10.1016/j.apenergy.2020.116269.

Castelvecchi, D. (2021). Electric cars and batteries: How will the world produce enough? *Nature*, *596*(7872), 336–339. https://doi.org/10.1038/d41586-021-02222-1.

Castrejon-Campos, O. (2022). Evolution of clean energy technologies in Mexico: A multi-perspective analysis. *Energy for Sustainable Development*, *67*, 29–53. https://doi.org/10.1016/j.esd.2022.01.003.

Chand, P., Thakkar, J. J., & Ghosh, K. K. (2020). Analysis of supply chain sustainability with supply chain complexity, inter-relationship study using delphi and interpretive structural modeling for Indian mining and earthmoving machinery industry. *Resources Policy*, *68*(June), Article 101726. https://doi.org/10.1016/j.resourpol.2020.101726.

Döscher, H., & Reiss, T. (2021). Graphene Roadmap Briefs (No. 1): Innovation interfaces of the Graphene Flagship. *2D Materials*, *8*(2), Article 022004. https://doi.org/10.1088/2053-1583/abddcc.

Döscher, H., Schmaltz, T., Neef, C., Thielmann, A., & Reiss, T. (2021). Graphene Roadmap Briefs (No. 2): Industrialization status and prospects 2020. *2D Materials*, *8*(2), Article 022005. https://doi.org/10.1088/2053-1583/abddcd.

Du, W., Geng, H., Yang, Y., Zhang, Y., Rui, X., & Li, C. C. (2019). Pristine graphene for advanced electrochemical energy applications. *Journal of Power Sources*, *437*(June), Article 226899. https://doi.org/10.1016/j.jpowsour.2019.226899.

El-Kady, M. F., Shao, Y., & Kaner, R. B. (2016). Graphene for batteries, supercapacitors and beyond. *Nature Reviews Materials*, *1*(7), 16033. https://doi.org/10.1038/natrevmats.2016.33.

European Commission. (2020a). Study on energy storage - Contribution to the security of the electricity supply in Europe (Issue March). https://ec.europa.eu/energy/sites/default/files/quarterly_report_on_european_electricity_markets_q4_2020.pdf.

European Commission. (2020b). Study on the EU's list of critical raw materials. *Factsheets on critical raw materials*. https://doi.org/10.2873/92480.

European Commission. (2021). *Study on the resilience of critical supply chains for energy security and clean energy transition during and after the COVID-19 crisis*. *https://doi.org/10.2833/946002*.

Freudenberg, M. (2003). Composite indicators of country performance: a critical assessment. *OECD science, technology and industry working papers. 16*. (pp. 35). https://doi.org/10.1787/405566708255.

Gardner, P., Jones, F., Rowe, M., Nouri, A., van de Vegte, H., Breisig, V., Linden, C., & Pütz, T. (2016). WORLD ENERGY COUNCIL World Energy Resources. https://www.worldenergy.org/wp-content/uploads/2016/03/Resources-E-storage-report-2016.02.04.pdf.

Gbededo, M. A., & Liyanage, K. (2020). Descriptive framework for simulation-aided sustainability decision-making: A Delphi study. *Sustainable Production and Consumption*, *22*, 45–57. https://doi.org/10.1016/j.spc.2020.02.006.

Ghiron, L., Shillingi, L., Kabiswa, C., Ogonda, G., Omimo, A., Ntabona, A., Simmons, R., & Fajans, P. (2014). Beginning with sustainable scale up in mind: Initial results from a population, health and environment project in East Africa. *Reproductive Health Matters*, *22*(43), 84–92. https://doi.org/10.1016/S0968-8080(14)43761-3.

Gumfekar, S. P. (2018). Graphene-based materials for clean energy applications. *Nanomaterials for green energy* (pp. 351–383). Elsevier. https://doi.org/10.1016/B978-0-12-813731-4.00011-4.

Hache, E., Seck, G. S., Simoen, M., Bonnet, C., & Carcanague, S. (2019). Critical raw materials and transportation sector electrification: A detailed bottom-up analysis in world transport. *Applied Energy*, *240*(November 2018), 6–25. https://doi.org/10.1016/j.apenergy.2019.02.057.

Hall, A., & Dijkman, J. (2019). Public agricultural research in an era of transformation: The challenge of agri-food system innovation. (p. IX + 67 pp.)https://cas.cgiar.org/isdc/publications/public-agricultural-research-era-transformation-challenge-agri-food-system.

Hassoun, J., Bonaccorso, F., Agostini, M., Angelucci, M., Betti, M. G., Cingolani, R., Gemmi, M., Mariani, C., Panero, S., Pellegrini, V., & Scrosati, B. (2014). An advanced lithium-ion battery based on a graphene anode and a lithium iron phosphate cathode. *Nano Letters*, *14*(8), 4901–4906. https://doi.org/10.1021/nl502429m.

How, Y. Y., Numan, A., Mustafa, M. N., Walvekar, R., Khalid, M., & Mubarak, N. M. (2022). A review on the binder-free electrode fabrication for electrochemical energy storage devices. *Journal of Energy Storage*, *51*(February), Article 104324. https://doi.org/10.1016/j.est.2022.104324.

Huang, K. J., Ceder, G., & Olivetti, E. A. (2021). Manufacturing scalability implications of materials choice in inorganic solid-state batteries. *Joule*, *5*(3), 564–580. https://doi.org/10.1016/j.joule.2020.12.001.

Huang, K. J., Li, L., & Olivetti, E. A. (2018). Designing for manufacturing scalability in clean energy research. *Joule*, *2*(9), 1642–1647. https://doi.org/10.1016/j.joule.2018.07.020.

Kakaei, K., Esrafili, M. D., & Ehsani, A. (2019). Graphene-based electrochemical supercapacitors. *Interface science and technology*. *Vol. 27*. (pp. 339–386). https://doi.org/10.1016/B978-0-12-814523-4.00009-5.

Kauling, A. P., Seefeldt, A. T., Pisoni, D. P., Pradeep, R. C., Bentini, R., Oliveira, R. V. B., Novoselov, K. S., & Castro Neto, A. H. (2018). The worldwide graphene flake

production. *Advanced Materials*, *30*(44), Article 1803784. https://doi.org/10.1002/adma.201803784.
Klerkx, L., Aarts, N., & Leeuwis, C. (2010). Adaptive management in agricultural innovation systems: the interactions between innovation networks and their environment. *Agricultural Systems*, *103*(6), 390–400. https://doi.org/10.1016/j.agsy.2010.03.012.
Kong, W., Kum, H., Bae, S. H., Shim, J., Kim, H., Kong, L., Meng, Y., Wang, K., Kim, C., & Kim, J. (2019). Path towards graphene commercialization from lab to market. *Nature Nanotechnology*, *14*(10), 927–938. https://doi.org/10.1038/s41565-019-0555-2.
Koyamparambath, A., Santillán-Saldivar, J., McLellan, B., & Sonnemann, G. (2022). Supply risk evolution of raw materials for batteries and fossil fuels for selected OECD countries (2000–2018). *Resources Policy*, *75*, Article 102465. https://doi.org/10.1016/j.resourpol.2021.102465.
Lach, J., Wróbel, K., Wróbel, J., Podsadni, P., Czerwiński, A., & <collab>Commission, E. collab (2018). *Towards the battery of the future. Vol. 23.*. https://doi.org/10.2779/674936 Issue March.
Ladrón-de-Guevara, A., Boscá, A., Pedrós, J., Climent-Pascual, E., de Andrés, A., Calle, F., & Martínez, J. (2019). Reduced graphene oxide/polyaniline electrochemical supercapacitors fabricated by laser. *Applied Surface Science*, *467–468*(June 2018), 691–697. https://doi.org/10.1016/j.apsusc.2018.10.194.
Landeta, J., & Barrutia, J. (2011). People consultation to construct the future: A Delphi application. *International Journal of Forecasting*, *27*(1), 134–151. https://doi.org/10.1016/j.ijforecast.2010.04.001.
Landeta, J., Barrutia, J., & Lertxundi, A. (2011). Hybrid Delphi: A methodology to facilitate contribution from experts in professional contexts. *Technological Forecasting and Social Change*, *78*(9), 1629–1641. https://doi.org/10.1016/j.techfore.2011.03.009.
Larrue, P.(. O. E. C. D). (2021). The design and implementation of mission-oriented innovation policies: A systemic policy approach to address societal challenges. *OECD science, technology and industry policy papers. 100.* (pp. 1–22).
Leeuwis, C., & Aarts, N. (2011). Rethinking communication in innovation processes: Creating space for change in complex systems. *The Journal of Agricultural Education and Extension*, *17*(1), 21–36. https://doi.org/10.1080/1389224X.2011.536344.
Levchenko, I., Ostrikov, K. K., Zheng, J., Li, X., Keidar, M., & Teo, K. B. K. (2016). Scalable graphene production: Perspectives and challenges of plasma applications. *Nanoscale*, *8*(20), 10511–10527. https://doi.org/10.1039/c5nr06537b.
Lin, L., Peng, H., & Liu, Z. (2019). Synthesis challenges for graphene industry. *Nature Materials*, *18*(6), 520–524. https://doi.org/10.1038/s41563-019-0341-4.
Liu, T., Zhang, L., Cheng, B., Hu, X., & Yu, J. (2020). Holey graphene for electrochemical energy storage. *Cell Reports Physical Science*, *1*(10), Article 100215. https://doi.org/10.1016/j.xcrp.2020.100215.
Loo, R. (2002). The Delphi method: A powerful tool for strategic management. *Policing: An International Journal of Police Strategies & Management*, *25*(4), 762–769. https://doi.org/10.1108/13639510210450677.
Lu, Y., Lu, Y., Niu, Z., & Chen, J. (2018). Graphene-based nanomaterials for sodium-ion batteries. *Advanced Energy Materials*, *8*(17), 1702469. https://doi.org/10.1002/aenm.201702469.
Marinaro, M., Bresser, D., Beyer, E., Faguy, P., Hosoi, K., Li, H., Sakovica, J., Amine, K., Wohlfahrt-Mehrens, M., & Passerini, S. (2020). Bringing forward the development of battery cells for automotive applications: Perspective of R&D activities in China, Japan, the EU and the USA. *Journal of Power Sources*, *459*(March), Article 228073. https://doi.org/10.1016/j.jpowsour.2020.228073.
Mauler, L., Duffner, F., & Leker, J. (2021). Economies of scale in battery cell manufacturing: The impact of material and process innovations. *Applied Energy*, *286*, Article 116499. https://doi.org/10.1016/j.apenergy.2021.116499.
Meelen, T., Truffer, B., & Schwanen, T. (2019). Virtual user communities contributing to upscaling innovations in transitions: The case of electric vehicles. *Environmental Innovation and Societal Transitions*, *31*(August 2018), 96–109. https://doi.org/10.1016/j.eist.2019.01.002.
Moreno-Fernández, G., Boulanger, N., Nordenström, A., Iakunkov, A., Talyzin, A., Carriazo, D., & Mysyk, R. (2021). Ball-milling-enhanced capacitive charge storage of activated graphene in aqueous, organic and ionic liquid electrolytes. *Electrochimica Acta*, *370*, Article 137738. https://doi.org/10.1016/j.electacta.2021.137738.
Moreno-Fernández, G., Granados-Moreno, M., Gómez-Urbano, J. L., & Carriazo, D. (2020). Phosphorus-functionalized graphene for lithium-ion capacitors with improved power and cyclability. *Batteries & Supercaps*, Article batt.202000247. https://doi.org/10.1002/batt.202000247.
Okoli, C., & Pawlowski, S. D. (2004). The Delphi method as a research tool: An example, design considerations and applications. *Information & Management*, *42*(1), 15–29. https://doi.org/10.1016/j.im.2003.11.002.
Olabi, A. G., Abdelkareem, M. A., Wilberforce, T., & Sayed, E. T. (2021). Application of graphene in energy storage device – A review. *Renewable and Sustainable Energy Reviews*, *135*(September 2020), Article 110026. https://doi.org/10.1016/j.rser.2020.110026 Issue March.
Patel, A., Loufakis, D., Flouda, P., George, I., Shelton, C., Harris, J., Oka, S., & Lutkenhaus, J. L. (2020). *Carbon nanotube/reduced graphene oxide/aramid nanofiber structural supercapacitors. https://doi.org/10.1021/acsaem.0c01926.*
Pavel, C. C., & Blagoeva, D. (2017). *Materials impact on the EU's competitiveness of the renewable energy, storage and e-mobility sectors.* European Union - Joint Research Centre. https://doi.org/10.2760/83521.
Peng, L., Fang, Z., Zhu, Y., Yan, C., & Yu, G. (2018). Holey 2D nanomaterials for electrochemical energy storage. *Advanced Energy Materials*, *8*(9), 1702179. https://doi.org/10.1002/aenm.201702179.
Probst, L., Frideres, L., Pedersen, B., & Clarke, S. (2015). Advanced materials the graphene revolution. *Business Innovation Observatory* https://ec.europa.eu/docsroom/documents/13427/attachments/1/translations/en/renditions/nativehttps://ec.europa.eu/docsroom/documents/13427/attachments/1/translations/en/renditions/native.
Raccichini, R., Varzi, A., Passerini, S., & Scrosati, B. (2015). The role of graphene for electrochemical energy storage. *Nature Materials*, *14*(3), 271–279. https://doi.org/10.1038/nmat4170.
Rogers, E. M. (1962). *Diffusion of innovations* (1st ed.). Free Press of Glencoe.
Rosenthal, J., Quinn, A., Grieshop, A. P., Pillarisetti, A., & Glass, R. I. (2018). Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environment goals. *Energy for Sustainable Development*, *42*, 152–159. https://doi.org/10.1016/j.esd.2017.11.003.
Salazar-Elena, J. C., Guimón, J., López, A., Muñoz, P. S., & Landeta, J. (2020). *MODELOS DE INNOVACIÓN ABIERTA: UNA APROXIMACIÓN AUTONÓMICA. https://doi.org/10.13140/RG.2.2.21886.00326.*
Sauer, D. U. (2015). Classification of storage systems. *Electrochemical energy storage for renewable sources and grid balancing* (pp. 13–21). Elsevier. https://doi.org/10.1016/B978-0-444-62616-5.00002-4.
Schmalz, U., Spinler, S., & Ringbeck, J. (2021). Lessons learned from a two-round Delphi-based scenario study. *MethodsX*, *8*, Article 101179. https://doi.org/10.1016/j.mex.2020.101179.
Schut, M., Leeuwis, C., & Thiele, G. (2020). Science of Scaling: Understanding and guiding the scaling of innovation for societal outcomes. *Agricultural Systems*, *184*(April), Article 102908. https://doi.org/10.1016/j.agsy.2020.102908.
Shapira, P., Gök, A., & Salehi, F. (2016). Graphene enterprise: Mapping innovation and business development in a strategic emerging technology. *Journal of Nanoparticle Research*, *18*(9). https://doi.org/10.1007/s11051-016-3572-1.
Sivaram, V., Dabiri, J. O., & Hart, D. M. (2018). The need for continued innovation in solar, wind, and energy storage. *Joule*, *2*(9), 1639–1642. https://doi.org/10.1016/j.joule.2018.07.025.
U.S. Department of Energy. (2020). *Energy storage grand challenge energy storage market report 2020.* Technical(December)*65*.U.S. Department of Energy https://www.energy.gov/sites/default/files/2020/12/f81/Energy Storage Market Report 2020_0.pdf.
van Audenhove, L., & Donders, K. (2019). Talking to people III: Expert interviews and elite interviews. *The Palgrave handbook of methods for media policy research* (pp. 179–197). Springer International Publishing. https://doi.org/10.1007/978-3-030-16065-4_10.
van Mierlo, B., Janssen, A., Leenstra, F., & van Weeghel, E. (2013). Encouraging system learning in two poultry subsectors. *Agricultural Systems*, *115*, 29–40. https://doi.org/10.1016/j.agsy.2012.10.002.
Vargo, S. L., Akaka, M. A., & Wieland, H. (2020). Rethinking the process of diffusion in innovation: A service-ecosystems and institutional perspective. *Journal of Business Research*, *116*(December 2018), 526–534. https://doi.org/10.1016/j.jbusres.2020.01.038.
Vernon, W. (2009). The Delphi technique: A review. *International Journal of Therapy and Rehabilitation*, *16*(2), 69–76. https://doi.org/10.12968/ijtr.2009.16.2.38892.
von der Gracht, H. A. (2012). Consensus measurement in Delphi studies. *Technological Forecasting and Social Change*, *79*(8), 1525–1536. https://doi.org/10.1016/j.techfore.2012.04.013.
Wigboldus, S. (2016). *Theory of scaling.* Wageningen UR.
Wigboldus, S., Klerkx, L., Leeuwis, C., Schut, M., Muilerman, S., & Jochemsen, H. (2016). Systemic perspectives on scaling agricultural innovations.A review. *Agronomy for Sustainable Development*, *36*(3), 46. https://doi.org/10.1007/s13593-016-0380-z.
Williams, R. H. (2001). Addressing challenges to sustainable development with innovative energy technologies in a competitive electric industry. *Energy for Sustainable Development*, *5*(2), 48–73. https://doi.org/10.1016/S0973-0826(08)60269-0.
Wong, S. I., Sunarso, J., Wong, B. T., Lin, H., Yu, A., & Jia, B. (2018). Towards enhanced energy density of graphene-based supercapacitors: Current status, approaches, and future directions. *Journal of Power Sources*, *396*(April), 182–206. https://doi.org/10.1016/j.jpowsour.2018.06.004.
Wu, Z. -S., Zhou, G., Yin, L. -C., Ren, W., Li, F., & Cheng, H. -M. (2012). Graphene/metal oxide composite electrode materials for energy storage. *Nano Energy*, *1*(1), 107–131. https://doi.org/10.1016/j.nanoen.2011.11.001.
Ye, R., & Tour, J. M. (2019). Graphene at fifteen. *ACS Nano*, *13*(10), 10872–10878. https://doi.org/10.1021/acsnano.9b06778.
Zhang, Y., Gao, Z., Song, N., He, J., & Li, X. (2018). Graphene and its derivatives in lithium–sulfur batteries. *Materials Today Energy*, *9*, 319–335. https://doi.org/10.1016/j.mtener.2018.06.001.