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PERSPECTIVE

Building a community lightsource meta-infrastructure to accelerate battery innovation in Europe

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Abstract

Breakthroughs in battery research are imperative to provide society with batteries that are safe and sustainable, have a high energy density, and have a long cycle life at low cost. Recent advances in research methodologies, the emergence of new market opportunities, and strategic funding schemes have allowed not only large, but also small companies, universities, and public research organizations to play an increasingly significant role in the advancement of battery technology. Challenges in battery technology development are multifaceted; therefore, a collaborative approach is crucial to bring together various stakeholders and ensure access to the full range of technical and scientific expertise. To grasp the core properties of electrode materials, electrolytes, and interfaces and to identify the mechanisms of battery degradation and failure, a multidisciplinary analytical approach is crucial. This strategy relies on the unique and complementary potential of advanced characterization techniques available at synchrotron and x-ray free electron laser facilities. Science-to-industry interactions are expected to increase the development of new standardized setups to approach realistic *operando* conditions. Therefore, rapid access to instruments, including high-throughput *ex-situ*, *in-situ* and *operando* capabilities, is key to accelerating the development of safe and sustainable batteries. The purpose of this paper is to discuss how the characterization needs of the battery community can be met by establishing a collaboration network based on a meta-infrastructure model, where the emphasis will be on collaboration and the sharing of experience and data. The proposed methodology considers the urgency in the battery community

and the necessary technical developments to reach the scope of collaboration and focuses in particular on the needs for standardization, big data challenges, and open data approaches.

1. Introduction

Batteries are a key technology in the pursuit of reducing the dependence on fossil fuels that has contributed to climate changes due to greenhouse gas emissions. As society moves towards 'clean' wind and solar energy sources and electric vehicles [1], the demand for batteries is growing rapidly [2]. Currently, the market is dominated by Li-ion batteries, which are nowadays approaching their performance and cost limits. To keep up with demands for greenhouse gas neutrality, high energy density and long cycle life, low costs, improved safety and sustainability, as well as efficient recycling methods, significant breakthroughs in battery research are imperative [3]. As a result, scientists are today exploring a range of new materials and manufacturing processes, using various technologies, strategies and tools [4–6].

Historically, the field has been dominated by a few large companies. In recent years, a noticeable shift towards a more diverse ecosystem has occurred. Smaller companies, universities, and public research organizations have increasingly played a significant role in the advancement of battery technology. This shift is driven by several factors, including increased access to funding, advances in research methodologies, and the emergence of new market opportunities, such as electric vehicles and grid-scale energy storage. Navigating this dynamic and sometimes unpredictable landscape requires adaptability, forward thinking strategies, and collective effort. In this context, long-term large-scale research initiatives at the European level, such as BATTERY 2030+[7] or Alistore-ERI [8], as well as national initiatives, are instrumental in fostering innovation and collaboration by bringing together diverse stakeholders to advance battery research and development, attract talent, and ensure access to the expertise needed to address challenges in the field.

Such an innovative ecosystem is essential as batteries are complex systems organized hierarchically, requiring the integration of various components across different length scales. The challenges in battery technology are multifaceted and inventive solutions are needed to overcome them. Battery performance critically depends on the properties of the electrode/electrolyte interface, where charge separation and electrochemical reactions occur. The evolution of these interfaces under operating conditions is determined by the electrode and electrolyte reactivity, controlled by surface chemistry and electrochemical potential, and affects all functional parameters of batteries, including power and long-term stability. Therefore, in order to improve batteries, a detailed understanding of the chemical reactions, mass transport, and electronic transfer processes at the interface that lead to electrode and electrolyte alterations and degrade the battery performance is essential. The irreversible electrolyte and electrode changes are rather complex and require qualitative and quantitative information, which when possible should be obtained under realistic operating conditions, both in surface and bulk regions, and on relevant time and length scales.

Addressing all these manyfold challenges calls for a multidisciplinary approach based on complementary advanced characterization tools and techniques. This includes understanding the fundamental properties of electrode materials, electrolytes, and interfaces, identifying battery degradation mechanisms, and validating theoretical models and simulations of battery behavior. These processes span various time and length scales, from sub-millisecond electrochemical processes to years of functional lifetime, and from the atomic level to the overall device structure. A comprehensive characterization strategy can greatly benefit from large-scale research infrastructures, which provide advanced analytical tools not commonly accessible in standard laboratory settings, like synchrotron or neutron facilities [5].

Neutron sources offer unique advantages for probing light elements such as lithium and hydrogen, enabling non-destructive, bulk-sensitive investigations of (nano) structural evolution, ionic diffusion, and interfacial processes under realistic *operando* conditions [9–11]. Additionally, specialized characterization centers equipped with high-resolution transmission electron microscopy (HR-TEM) and solid-state nuclear magnetic resonance (ssNMR) further enhance these analyses [12]. HR-TEM provides atomic-scale structural and chemical details that are essential for elucidating interfacial phenomena and degradation mechanisms [13]. ssNMR delivers unparalleled insights into local chemical environments and ion dynamics within both crystalline and amorphous electrode or electrolyte materials [14]. When integrated in multi-modal and correlative workflows, these techniques collectively strengthen the analytical capabilities required to accelerate innovation in battery research [15].

Synchrotron sources offer a wide range of different techniques, classified in three main categories: spectroscopies, diffraction/scattering, and imaging. In the last decade, x-ray spectroscopies have been more and more exploited for unveiling the functional mechanisms in batteries [16]. Thanks to the high synchrotron flux, constant tuneable photon energy, and the relatively high penetration depth of x-rays, typically both *ex-situ* and *operando* experiments can be foreseen to probe (electro)chemical processes including charge compensation mechanisms and material degradation pathways [17–27]. In brief, (a) x-ray absorption spectroscopy (XAS) provides chemical information, and insights on the electronic and/or local structural properties of the material. XAS can be surface or bulk sensitive depending on the measurement approach—collecting electron or photon (drain current or fluorescence/transmitted photons) signals. It is heavily used for probing SEI formation [28, 29] as well as bulk redox [30, 31] processes. Examples found in literature reveal charge compensation mechanisms in several different systems, from the close to commercial solutions (e.g. 3d transition metal oxide cathodes [32–35]) to more exotic, potentially next generation systems (e.g. 4d or 5d transition metal oxide cathodes [36, 37], sulphur-based batteries [38, 39], beyond-Li-technology [40–42], etc). (b) X-ray photoelectron spectroscopy (XPS) allows for *ex-situ*, *in-situ*, and *operando* monitoring of the interface reactions at working electrodes with both solid [43–46] and liquid electrolytes [47], utilizing the near-ambient pressure approach. This approach can be also exploited for probing Me-air batteries [48–50] or combining it with, e.g. the dip-pull mode [51, 52] to probe the liquid–solid interface. (c) x-ray microscopy, spectromicroscopy and ptychography are very powerful in morphological and compositional analysis down to the nanoscale and under *operando* conditions as well [21, 53, 54]. Their exploitation not only helps to visualize the investigated phenomena, but can also allow to identify cause-effects relationships [55]. (d) X-ray diffraction (XRD) [56–58], including scanning microbeam techniques [59–61], potentially coupled to computed tomography (XRD-CT) [62, 63], reveals crystal structural variations during insertion and deinsertion processes, whereas small-angle and wide-angle x-ray scattering (SAXS) can be used to follow variations of nanostructured species or components, nanoparticle size distribution or pores size at the electrode [64]. (e) Micro and nanotomographic methods are key to image the interior of cells while working, providing morphological and structural insights at cell and component level [65], as well as ultimate details at material level on particles cracking, heterogeneous aging, dendrite formation, metal plating, chemomechanics, etc [66–69]. Time-resolved CT for large imaging can be also exploited to assess the safety of commercial products [70]. One of the strengths of large-scale x-ray facilities is that the same sample can be characterized by a combination of x-ray-based methods, finally uncovering the properties of the battery system under various working conditions.

X-ray free electron lasers (XFELs) with femtosecond pulse duration and high repetition rate, bring a new dimension to the table, enabling the investigation of ultra-fast time-scale dynamics (e.g. electron transfer). XFEL methods can enhance our understanding of the functionalities of electrode materials and interfaces, their electronic distribution and charge compensation mechanisms, offering new opportunities to elucidate the coupling between changes in electronic configurations and structural dynamics during charge transfer and ion transport. These phenomena are expected to affect the achievable energy storage capacity and its retention. Moreover, XFELs can help identify transient species that arise during charge and discharge cycles, providing a deeper understanding of battery behavior.

As the use of synchrotron tools for analysis is methodologically complicated, close collaboration between universities, industry partners, and synchrotron research teams are necessary for battery studies. Synchrotron experiments are often conducted on model systems with simplified compositions of electrode and electrolyte compared to real objects, to isolate species of interest, making less complicated data analysis. Often, there is a delay between the discovery of new materials with better performance and disclosure of the nature of their exact structure and chemistry by advanced synchrotron-based methods. This is caused by several factors, including (i) limited access to synchrotron and XFEL proposal schemes (granting the beamtime months after application), (ii) unwillingness to share know-how with a broader scientific community, including proposal reviewers and government scientists, (iii) challenges in data analysis of *operando* experiments, and (iv) the possible influence of the intense x-ray probe, as species generated by exposure to intense radiation could influence the outcome of the experiment. Moreover, the absence of a clear framework for the science and industry collaboration hinders the practical application of scientific findings for enhancing the performance of commercial devices.

Existing and novel synchrotron- and XFEL-based characterization techniques must be further developed to provide quantified data, multidimensional sets of results with quality-assessed observables, directly transferable to, and usable by, the community. This must be organized within community-driven meta-infrastructures incorporating common practices, rules and know-how, while setting the conditions for more standardized and integrated workflows designed to accelerate the data-to-end result speed and knowledge transfer. Battery-focused network of light sources in Europe figure 1 can bridge the battery community's needs for superior structure-chemistry-property investigations and materials screening studies, and propose new schemes for further advancing research in the field.

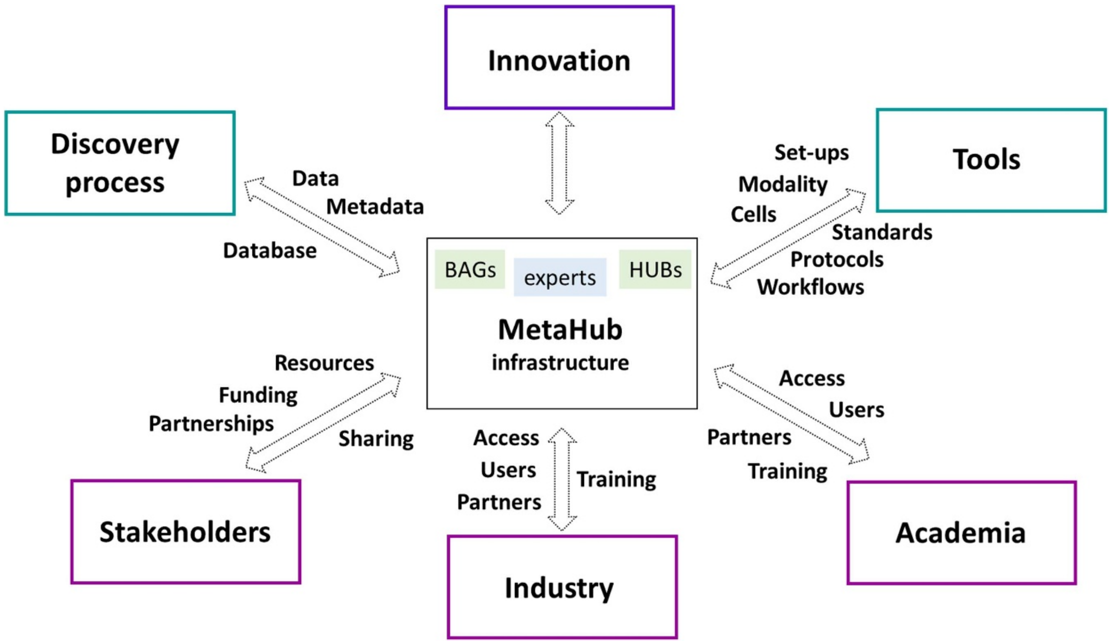

Figure 1. Meta-infrastructure scheme for advanced cooperation in x-ray science for batteries based on Block Allocation Groups (BAGs) and HUBs for developing community-tools. Challenges are to share data, skills and resources to accelerate the discovery and innovation process, and meet today's society needs for solving key industrial challenges. The meta-Hub connects to academia, industry and stakeholders, creating networks of users and partners, developing training, partnerships and funding schemes, as well as promoting access modes to the facilities and usage of standardized set-ups, modalities and workflows.

2. X-ray characterization needs of battery community

Key challenges in battery research which are best addressed by x-ray techniques include probing the reaction mechanism in the bulk and at the interfaces, including SEI formation and associated degradation pathways under operating conditions. *Ex-situ*/post-mortem studies generally provide only a limited view on the underlying processes as the electrochemical and chemical reactions taking place during cell operation may result in intermediates and products that are only stable under operating conditions and thus can usually not be identified by post-mortem analysis of cycled and subsequently disassembled cell components. In solid-state batteries, removing the sample from its high-pressure environment and exposing electrode surface to the atmosphere of a glove box containing traces of water and oxygen may result in unintended changes to the structure or chemistry due to relaxation effects and the reactive nature of the battery materials, which might include alkali metals. In batteries with polymer electrolytes, mechanical separation of the polymer from the current collector leads to disintegration of SEI making it impossible to probe its heterogeneous nature by *ex-situ* methods. Batteries with liquid electrolyte and Me-air batteries generate gaseous species during their operation, which can chemically react with electrode and electrolyte components, contributing to degradation mechanism. Thus, the methodologically correct way should focus on probing these processes under operating conditions, where the x-ray toolbox comes into play, with its complementary methods, combining surface and bulk sensitivity and sample environments developed for *operando* research. Synchrotron and XFEL-based analytical tools fully exploiting the brilliance of x-ray sources have proven to be a game changer, enabling *operando* studies at buried interfaces at the relevant time scales.

Rapid access to all the instruments, enabling necessary characterization techniques, is critical for accelerating the development of sustainable and safe batteries. This implies provision of fast, repetitive and multi-modal access to large-scale infrastructures (photon and neutron facilities) and a general collaborative framework between research institutions. In particular, fundamental for an efficient use of available research infrastructure and avoiding the waste of resources are the capability of identifying the set of characterization tools that is best suited to answer a specific scientific question, and the frameworks for coordinating multi-technique, multi-site and multi-partner experiments. In this context, the less available exotic techniques may become the target. This implies the integration of a large research community in a structured manner, where complementary knowledge, skills, practices and tools are shared for a common objective. The transition from competitive isolated researchers towards large research groups sharing know-how is fundamental for quick and robust developments. Such better exploitation of the resources has the additional advantage of providing tools which could also be offered to other areas of high societal relevance.

This transition presents a number of challenges. First, the multi-modal approach, including a combination of characterization tools for adequately addressing complex scientific questions, entails a collaboration of experts in different techniques. Second, the massive production of data generated by the multi-modal complementary approach with *operando* or imaging capabilities implies expansions in data analysis capabilities. Furthermore, ongoing advancements in artificial intelligence necessitate its implementation for efficient and comprehensive data analysis, including automated identification of correlations. Finally, the need to accelerate battery research creates straightforward science-to-industry interactions that incorporate scientific results into the development pipeline of new devices.

The techniques which provide access to generally needed and routinely obtained information, such as XRD, XAS, XPS and CT, need to be first standardized, from data acquisition to their analysis, profiting from the deep knowledge developed in the past years by the different experts of each technique. This also implies the standardization of the analytical setups, ranging from cell materials, to electrochemical testing protocols for acquisition and beam modulation assessments, which are needed to ensure reproducible results. Indeed, the general absence of standardization could make the direct correlative/multimodal approach between systems/instruments unreliable. Moreover, standardization is expected to simplify the technical aspects during the preparation and execution of experiments, avoiding empirical measurement artifacts because of the lack of knowledge.

Further, development of (*operando*) interface-sensitive techniques tailored for battery research is needed, as critical phenomena occur at various interfaces within the cell. Significant progress has been made to access the interfaces by increasing the interfacial sensitivity of classically bulk-sensitive methods (including grazing incidence XRD or improving surface-to-bulk ratio by ball-milling the samples) or by adapting existing surface-sensitive methods for probing the buried interfaces (for instance, measuring interfaces through x-ray and electron-transparent films or windows). However, new workflows will be required for adapting state-of-the-art techniques (e.g. advanced x-ray spectroscopies such as resonant inelastic x-ray scattering) to *operando* conditions.

One of the greatest challenges for the x-ray community working with battery materials is understanding, mitigating and evaluating beam modulation effects (also commonly referred to as 'beam damage' or 'beam inhibition') [71–73]. Even though the existence of such measurement artifacts has been known for decades, still there are no clear, universal and well-established mitigation strategies. The situation suddenly became even more complicated when the subject was moved to *operando* studies, where the intense x-rays induce the radiolysis of electrolyte species by generating radical species that are integrated in the reaction mechanisms, compromising the fidelity and quality of analysis. These effects can be even more dangerous as in some situations they are hidden: in fact, the electrochemical response represents the whole full cell or a whole electrode (depending on the probed cell configuration: 2 or 3 electrode cells, full or half-cell, etc), but only a small part could be affected by the beam (the size of which can go down to tens of nm^2), leading to discrepancies between phenomena observed by x-rays and the phenomena responsible for the electrochemical performance of the whole cell.

Finally, science-to-industry interactions are important in the development of battery technologies, as one of the main goals of researchers is to improve and accelerate industrial uptake of these technologies. To achieve this objective, it is anticipated that there will be a push to speed up the development of new standardized setups to approach realistic *operando* conditions, *in-situ* synthesis, and to address safety aspects. Prime in this context is the development of high-throughput setups and automated data analysis pipelines, allowing fast screening of newly developed materials to identify the material controlling parameters. Another example is the need for holistic studies of industrial battery cells, where high-energy x-ray techniques provide insights into the (electro)chemical inhomogeneities and aging mechanisms, both important aspects for battery commercialization. In addition, a closer collaboration will allow scientists to also focus on other important aspects of material properties, such as sustainability and recyclability. In turn, this requires to create new programs for training of true cross-disciplinary specialists serving as a bridge between fundamental science at synchrotron and XFEL facilities or universities, and industry partners.

The League of European Accelerator-based Photon Sources (LEAPSs) [74] is uniquely positioned to bridge the needs of the battery community with cutting-edge x-ray instrumentation and expertise. The 16 LEAPS facilities, with advanced accelerator technologies, feeding numerous research instruments with advanced data handling infrastructures, can effectively support complicated multi-modal workflows and high-throughput measurements. The user-centered organization of the access and long-term collaborations with various industries can help to accelerate a streamline engagement with battery research organizations, technology centers and production. In addition, the internal LEAPS organization allows coordinating a multi-facility access, needed to fully embrace the research and innovation potential in battery field.

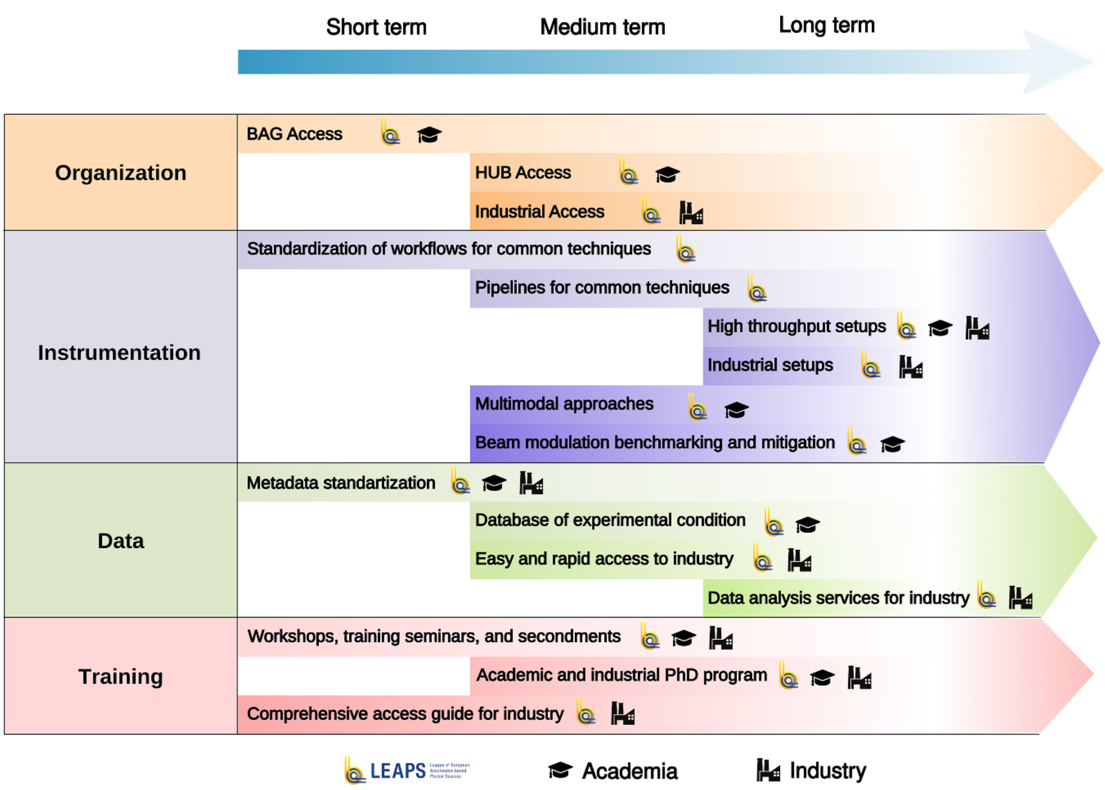

Figure 2. Roadmap timeline showing the important steps for the development of the effective meta-infrastructure. The involved stakeholders are indicated for each step.

3. Proposed collaboration roadmap between LEAPS and battery community

The roadmap builds on four basic pillars: Organization, Instrumentation, Data and Training. The timeline for LEAPS activities related to these pillars and their temporal dependence is provided in figure 2.

Organization We foresee that the characterization needs of the battery community elaborated in the previous section can be met by establishing a collaboration network based on Block Allocation Group (BAG) and HUB models, as first proposed in [5]. In this model, LEAPS facilities provide the battery community with accelerated material discovery possibilities by coordinating activities related to complex multi-modal investigations, incorporating community-tools as standards and protocols.

In the BAG scheme, battery researchers that require access to synchrotron-based techniques (XRD, SAXS, CT and XAS, XPS, XRF, including microscopy approaches as well) are grouped by technical interest (high-throughput, specific *operando* experiments) with LEAPS providing access to the required techniques in an organized manner. The BAG is expected to use standard setups and standardized electrochemical cells, allowing the use the LEAPS instrumentation in the most efficient manner and also considering continuous improvements of the set-ups, prompted by the ongoing experiments. The BAG can be built around an instrument and specialized technique, or around an experimental setup which can be duplicated at other facilities according to the demand. This should optimize the structure, reducing the pressure on a single facility/instrument avoiding negative effects on user communities focused on other topics. In fact, other user communities will benefit from the better organization and portfolio of developed tools, from high-throughput *ex-situ* setups to state-of-the-art *operando* sample environments and automated data analysis pipelines. In particular the opportunities are optimized, since once the instrument and/or cell is set up, the BAG users will just change the samples without the need to re-set the instrument. Certain degrees of freedom will still be provided to accommodate special requests or measurements within the BAG, which is especially important for *operando* measurements. In addition, training and data analysis will be driven by experts in the BAG community, with the guidance of beamline scientists, significantly easing the pressure on LEAPS facilities experts and shortening the time between experiment and publication.

The HUB scheme is similar in the sense that it gathers the community to perform continuously experiments at LEAPS facilities in an organized manner, but the emphasis is on collaboration and sharing of data and experience. This mode is tailored to the complex research and multi-modal approach for fundamental investigations of problems and questions, where repeated and coordinated access to multiple instruments is needed to meaningfully address the problems in question. A pilot battery HUB has been implemented on the local scale in Grenoble to benchmark technical, scientific and organizational schemes [75]. The governance model included science-driven beamtime selection by the HUB board members. The path towards novel community-driven methods, standards and protocols was explored [58, 72, 76] in line with European-level initiatives toward materials acceleration platforms using AI-assisted integrated numerical and experimental workflows [77–79]. The HUB scientists defined the area of interest based on battery technology and/or fundamental phenomena in battery research, and together with the pilot facility, the most appropriate combination of techniques and instruments was set [61, 80–82].

Here we propose a new strategy where the LEAPS facilities together with HUB researchers deploy such methodologies at a larger scale, e.g. in a metaHUB infrastructure, with the diverse capabilities of the LEAPS facilities leveraged to provide complementary tools that can be selected on an ad hoc basis to address specific scientific questions. The organized long-term access to the instruments is set for limited period, or until the problem is solved, and the HUB experts organize the access within the HUB in the most efficient manner. For example, this may include performing several first-shot *ex-situ* experiments on disassembled cell components to understand pristine battery chemistry and its overall expected changes during operation, followed by *in-situ* experiments to tackle isolated chemical reactions (with the possibility to use another beamline for this task) and, if necessary, performing *operando* research based on the previously collected data. The experts in the HUB are expected to collaborate on the projects and provide their particular expertise within the HUB. Compared to the standard access mode, this scheme has several advantages [5]: (i) it facilitates and significantly speeds up multi-modal experimental workflows, (ii) it fosters collaboration and expertise sharing between HUB partners, accelerating the discovery process, and (iii) it improves the excellence of the selected experiments by passing the responsibilities to the HUB experts for the beamtime allocation. We foresee that several HUBs will be formed across LEAPS facilities, based on the particular phenomena in electrochemical science (e.g. alkali metal plating or high voltage degradation phenomena) or battery technology (e.g. metal–air or multivalent systems) since each phenomenon/technology requires a set of different tools to truly unravel its complexity, or industry-relevant topic (e.g. battery safety). We argue that this centralized and federated approach built on local initiatives is more efficient compared to the strictly local approach in the case of x-ray characterization at LEAPS facilities, given the limited access and more efficient use of shared resources. Although strictly local initiatives are excellent for multidisciplinary and competitive research, it is difficult to bridge the gap between facilities with different instruments and expertise needed for modern battery research. Given the need to establish a community-adopted quality assessment and reach more representative, reliable, and reproducible data and results in LEAPS facilities, the administrative overhead needed in this case is well justified.

Instrumentation Improving efficiency of standard measurements will require high-throughput instrumentation and long term access schemes through BAGs and HUBs. In the first phase, XRD and XAS could be considered for high-throughput measurements, as they are true workhorses in battery research. For both techniques, the measurement or experimental time needed to characterize several cells can be reduced by parallel measurements. For example, at the same time multiple batteries can be characterized during slow charging experiments, and *ex-situ* characterization can be streamlined by developing dedicated high-throughput setups [83]. This will require the use of dedicated, standardized cells and electrochemical protocols as described elsewhere [5], as well as dedicated instrument hardware and measurement protocols. Rigorous quality control schemes with well-defined, straightforward-to-measure, and unambiguous indicators are needed to compare the dataset from various instruments with different characteristics, such as different energy, energy bandwidth, detection systems and electrochemical cells.

Multi-modal HUB workflows will also foster the development of instrumentation for lesser-used techniques and multi-modal electrochemical cells for use on different instruments [5]. This will be unique for each HUB as the multi-modal workflows are specific for each scientific question. The acquisition schemes will also need to be adapted to the high flux available at 4th generation light sources, considering possible x-ray beam damage to the studied battery systems. Therefore, strong effort to address these issues has to be part of the LEAPS roadmap, including basic research, benchmarking and mitigation strategies. Round-robin analysis of standardized samples probed at various facilities can be envisioned to establish the beam and sample-dependent dose and dose rate effects. Defining the safe zones for battery investigation with no local disruption of the reactions and their kinetics could be established as a facility-agnostic tool. This must be defined across the various local hubs to insure a beneficial synergy, and must rely on defining common and overarching goals serving the global battery community needs. Quality-assessment procedures, standards and protocols for data acquisition and analysis, and single-entry open databases can be established at the metahub level, building on local initiatives and gathering their practices towards establishing community-adopted tools. A key mechanism is the implementation of a universal metric to determine the level of reliability, reproducibility and representativeness of a synchrotron experiment on batteries in terms of electrochemistry, beam evaluation and data [84].

Data Data pipelines are key elements for properly handling high-throughput investigations and standardization. First, the meta-data needs to be universal and readable by machines. In this respect, battery metadata ontologies based on those previously developed within the BIG-MAP project [85] will be implemented at LEAPS facilities to facilitate the interaction between the machine and the acquired data. This will further promote data sharing and will determine clear roles regarding data management and curation. Instrumental workflows for standard techniques will be complemented by automated data pipelines, allowing faster data treatment and classification. This will need to be implemented in a rolling fashion as most of the instruments have unique data acquisition schemes and data formats. However, such a development has to be orchestrated among LEAPS facilities to unify the final output. For multi-modal workflows, it is important that the data are in the form that facilitates correlative analysis. Therefore, experimental approaches that combine proper marking of the measurement area detectable by various probes and subsequent spatio-temporal data alignment have to be developed, as used in microscopy for instance.

In order to obtain meaningful, comparable and reproducible datasets, a LEAPS-wide database with properly stored metadata of experimental conditions of *operando* battery experiments will be implemented. Such database will be based on community ontologies, allowing not only to compare the experiments, but also to access information about beam conditions and dose to help better assessing the possible beam effects on the studied system. Such a robust approach is necessary to understand the origin of the x-ray probe damage and ultimately to ensure that the data are reproducible and least affected by the probe.

Training and intertwining Training and intertwining between LEAPS facilities and academia/industry is an important part of the integrated effort to accelerate the use of advanced characterization in the battery field. Initiatives such as common PhD programs among LEAPS facilities, academia and industry will be the cornerstone for further interactions providing a well-educated interdisciplinary workforce able to properly employ LEAPS facilities in battery-related research. Additionally, doctoral and post-doctoral researchers at LEAPS facilities benefit from daily interactions with a global community of users involved in pioneering research. This engagement not only deepens their scientific knowledge, but also creates opportunities for meaningful academic and industrial partnerships, thereby reinforcing the European innovation ecosystem. Particular attention shall be paid to the provision of training for industrial partners by LEAPS scientists/engineers and vice versa through large-scale and well-managed workshops, schools and reciprocal secondments. Training should cover all levels of technical expertise and management, providing a comprehensive bilateral understanding of both the advanced tools available at the facilities and the pressing challenges faced by industries. Normally, industrial PhDs are not trained for a role in industry. In future training programs, it would be beneficial to combine training in advanced and novel synchrotron and XFEL-based characterization techniques with training for a carrier as an industrial scientist. In addition to scientific skills, the students would learn how to lead, navigate within organizations and excel in communicating scientific results in an industrial setting. Investing in training industrial scientists is expected to enable return-on-investment in future industrial investments at large scale research infrastructure. The training program can be expanded to a mobility program for both beam scientists and scholars in academia, in order to build knowledge and understanding of all the three corners of the tripple helix contex.

Industry Industrial research in the field of advanced batteries is an important part of the commercialization of future technologies. LEAPS stands at a unique position figure 1 because it provides non-invasive characterization techniques which can be used to obtain information about the materials in laboratory-scale cells as well as commercial battery packs. These opportunities are still largely untapped by industry, but will be essential for R&D for a faster development of new battery chemistries. The LEAPS facilities are committed to fostering active engagement with industry, contributing to industrial developments and innovation. Using an extensive network and internal know-how, LEAPS identifies gaps in battery research where conventional laboratory techniques fall short, showcasing the unique capabilities of its advanced facilities. This proactive approach aligns cutting-edge research with industrial needs, driving innovation forward. One strategy for equipping new industrial users with the tools necessary for successful large-scale experiments is to involve expert academic users and encourage them to share their expertise and methodologies. We aim to encourage academic-industrial training partnerships, where interested industrial users, with the approval of the principal investigators, are invited to participate in experiments as observers or collaborators, providing hands-on experience and insight into the complexities, capabilities, and requirements of large-scale facility experiments. Likewise, the collaboration should extend into the other direction, allowing facility scientists and academic researchers to gain experience in an industrial R&D environment. This involvement offers valuable '*operando*' training, addressing critical skills such as sample preparation, experimental setup, and data analysis, key factors for success in large-scale research. By fostering these collaborations, LEAPS accelerates advancements in battery R&D and strengthens the European innovation ecosystem. Through bridging the gap between academia and industry, LEAPS is dedicated to cultivating a cohesive, collaborative user community that drives innovation forward in the field.

Furthermore, the potential to leverage industry expertise for the co-development of customized setups aimed at addressing critical challenges in the battery field is foreseen. These co-developed solutions shall be shared with the facility user community, fostering a stronger interconnected commitment between industry and academic R&D.

To nurture a long-term, profitable relationship between LEAPS facilities and industry by accommodating the industrial requirement of proprietary access, LEAPS needs to co-develop specific access modes and setups tailored for proper IP protection and automated data acquisition, analysis and easy data access. To transfer the LEAPS experience from academic development to industry, we seek to adapt concepts from fields that are already functioning in a fully commercial mode, such as macromolecular crystallography. Industry access has to be timed with the needs of proprietary R&D processes, including possibilities for rapid sample turnover. Fully developed data pipelines compatible with industrial standards need to be provided. Appropriate IP and confidentiality arrangements have to be made, following requirements for competitive proprietary and pre-competitive R&D. Technology transfer should be established by providing detailed workflows of coupling fundamental results, obtained at light sources, with battery modeling to enhance predictive capabilities. Additional workflows in industry should be established to incorporate the predicted results into current technology, for example, by fast screening of the device properties, with a fast feedback loop to LEAPS and battery scientists.

4. Conclusions

The fast development of battery technologies, essential for reducing the dependence on fossil fuels and mitigating climate change, requires a change in the scientific approaches applied to battery materials and cell development. Due to the intrinsic complexity of battery materials and their chemistries, addressing open scientific questions requires a multidisciplinary approach that integrates expertise across various fields. Achieving this goal requires a collaborative framework that unites stakeholders from industry, academia, and public research organizations.

In this framework, the complementary and unique capabilities offered by advanced characterization, such as synchrotron and XFEL-based techniques, electron microscopies, neutron techniques, and NMR, are invaluable. These tools can unlock critical insights into material behavior and cell performance. However, for further maximizing their potential, collaborative models like BAG and HUB networks, are required. These frameworks facilitate efficient, collective use of resources, ensuring that expertise and infrastructure are optimally exploited.

Finally, new methodologies for beamtime access, together with standardization of experimental protocols and data analysis processes, are crucial. Standardized practices not only accelerate the access to meaningful results, but also maintain reproducibility and comparability across studies, enhancing the impact of research outputs. Such an approach is necessary to drive efficient advancements in battery development, enabling a more sustainable future.

Data availability statement

No new data were created or analysed in this study.

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Author contribution statement

S L and J D conceived and coordinated the study. All authors contributed to the manuscript.

Conflicts of 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.

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