BATTERIES EUROPE SECRETARIAT

D1.4 - Position Paper on cross-cutting topics

Work Package 4 – Strengthening a holistic battery R&I ecosystem with synergistic efforts

Due date of deliverable: 30 April 2024

Actual submission date: 30 April 2024

Project Acronym	BEST
Call	HORIZON-CL5-2021-D2-01
Grant Agreement No.	101069676
Project Start Date	01-05-2022
Project End Date	30-04-2025
Duration	36 months

INFORMATION

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Reviewed by	Spyridon Pantelis (EERA)	2024-04-29
Approved by	Alessandro Romanello (EITInnoEnergy) – Project Coordinator	2024-04-30
Status	PU	

DISSEMINATION LEVEL

CO	Confidential	
CL	Classified	
PU	Public	x

VERSIONS

Date	Version	Author	Comment
26-04-2024	1.0	Spyridon Pantelis (EERA)	The first draft
30-04-2024	FINAL	Alessandro Romanello (EITInnoEnergy)	Final and submitted version

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676

ACKNOWLEDGEMENT

Batteries Europe Secretariat is an EU-funded project that has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676.

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EXECUTIVE SUMMARY

There is a critical imperative to address the clean energy transition from a **holistic and cross-sectorial perspective** with the goal to advancing clean energy research[1]. Such emphasis is evident in the priorities outlined in the SET Plan, underscoring the significance of addressing cross-cutting issues to expedite the development and deployment of clean and efficient energy technologies[2,3]. Within Priority 4, non-technological factors such as skills and sustainability are recognised as **pivotal facilitators for driving progress in battery technologies**, thereby bolstering EU competitiveness in the global battery sector.

Cross-cutting topics form the cornerstone of activities within the Batteries Europe ecosystem. In the past years **six cross-cutting Task Forces** have been actively engaged in facilitating collaboration among research and industry experts. Unlike the established Working Groups which is the core collaboration framework within Batteries Europe and mirror the distinct stages of the battery value chain (from raw materials to applications), the Task Forces focus on topics that extend beyond purely technological considerations. They prioritise pivotal cross-cutting topics crucial for the development of battery technology, which are integral to multiple aspects of the value chain. These topics encompass **Education & Skills, Digitalisation, Sustainability, Safety, Hybridisation, and Social Sciences & Humanities**, underscoring the comprehensive approach needed to advance battery technology effectively.

The Task Forces are operated in collaboration with the Batteries European Partnership Association (BEPA) and they are accessible and open for participants to join freely. As of April 2024, they have facilitated the **cooperation of over 350 experts**, fostering an inclusive environment for collaboration and knowledge exchange within the Batteries Europe ecosystem. With the aim of enhancing the integrated R&I ecosystem across these cross-cutting domains, the collaboration has led to the drafting of **six position papers**. These papers, included in the current publication, seek to highlight the R&I cross-cutting needs of the battery technology, offering **strategic guidance to policymakers at both European and national levels**. Additionally, they hold significant value not only for researchers and large enterprises but also for SMEs. These papers serve as valuable resources to inform, share knowledge, and foster new opportunities for collaboration across the battery industry, facilitating informed decision-making and driving innovation at various levels of engagement.

The current publication provides an updated version of the four existing position papers initially published in 2020 by the Task Forces focusing on Education & Skills, Digitalisation, Sustainability, and Safety. Additionally, it introduces two "new" Task Forces dedicated to Hybridisation and Social Sciences and Humanities. These newly established Task Forces illuminate relatively new and less explored avenues, laying the groundwork for accelerated and more comprehensive development in these vital domains within the battery industry.

[1] EERA White Paper on the Clean Energy Transition: https://mailchi.mp/eera-set/clean-energytransition
[2] COM(2023) 634 final of 20.10.2023 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0634
[3] European Commission, Directorate-General for Research and Innovation, SET plan interim evaluation final report, Publications Office of the European Union, 2022 https://data.europa.eu/doi/10.2777/939719

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Batteries Europe

Position paper

Education & Skills Task Force

April 2024

In cooperation with

BEPA

Batteries European Partnership Association

ACKNOWLEDGEMENT

Batteries Europe Secretariat is an EU-funded project that has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676.

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This project has received funding from the European Union’s Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

Acknowledgements: We would like to thank Spyridon Pantelis (EERA) for the overall coordination of the Task Forces, Alessandro Romanello (EIT InnoEnergy) as coordinator of Batteries Europe, and the BEPA Secretariat for their support in the operation of the Task Force. Special thanks to Fatima Ahmed, Adeola Adeoti, Lucia Sardone (CLERENS), and Maria Luisa Fernandez Vanoni (EERA) for editorial support. We would also like to acknowledge the inputs and considerations from the European Commission, the Batteries Europe Secretariat and Batteries Europe Advisory Board.

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ABBREVIATIONS AND ACRONYMS

Abbreviation	Definition
ALBATTS	The Alliance for Batteries Technology, Training and Skills
BEEC	Batteries Europe Education Commission
BEPA	Battery European Partnership Association
CVET	Continuing Vocational Education
EHEA	European Higher Education Area
ESS	Energy Storage System
GWh	Gigawatt hour
IVET	Initial Vocational Education
ICE	Internal Combustion Engines
LIB	Lithium-Ion Batteries
MESC	Materials for Energy Storage and Conversion
MOOC	Massive Open Online Course
SME	Small and medium-size enterprises
SSbD	Safe and Sustainable by Design
STEM	Science, Technology, Engineering and Mathematics
TTT	Train the Trainers
xEV	Electric Vehicle

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1 INTRODUCTION AND MOTIVATION

Addressing global challenges of climate change and human and environmental health urges continuous research, development, and innovation. At the same time, it also fuels the urgency to develop a highly skilled workforce, adapted to emerging technologies, whilst also driving the industrial sectors towards adapting to future socioeconomic realities. This should help avoid talent shortages by 2030 and beyond.

The European Commission highlights investment in education, science, technology, research, innovation, and digitalisation as a prerequisite for achieving a sustainable EU economy that meets the Sustainable Development Goals of the United Nations[1]. Additionally, Horizon Europe (HE) reflects on education and training for high value skills, productivity, and growth as well as fostering the EU digital transformation.

The global battery demand, driven by electric mobility (xEVs), stationary storage (ESS), and other applications, will dramatically expand the need for battery cells from 250-300 GWh in 2020 to at least 2.5-3 TWh towards 2030 and more than 10 TWh beyond[2]. The European Commission launched the European Battery Alliance[3] in October 2017 to address this industrial challenge. In Europe[1][4], the demand will increase from currently 30 - 50 GWh to 150 - 300 GWh in 2025, and at least 400 - 1000 GWh around 2030. That will be covered by the setting up of battery production capacities in Europe both by overseas companies but also, increasingly, by European cell manufacturers. Developing battery storage and mobility is one of the key pillars of the European Green Deal with strong incentives for the creation of a European Battery Value Chain. The main open question is how successful EU headquartered manufacturers will be and how production will be distributed between European and other world regions.

A **skilled workforce** along the entire Battery Value Chain will therefore be decisive for European companies and industries to be competitive and sustainable[5]. It is estimated that the job market impact of the establishment of a GWh battery production facility and the full battery ecosystem around is on the level of several hundred people directly and much higher when including also indirect employment effects. Considering the total Battery Value Chain from raw materials, components, cells to battery integration (e.g. in xEVs) and recycling as well as equipment manufacturing the direct and indirect employment effects in Europe are estimated to be 800.000 around 2025, 1.5 Mio by 2030[2] [2,6]. While there is a leverage effect of about 10 (i.e. with 1 battery expert needed in total about 10 direct and indirect jobs along the entire Battery Value Chain are connected) this means that, several hundreds of thousands of people with knowledge and skills on different aspects related to batteries

[1] *Europe*: a wide definition for European countries, both EU member countries and candidate countries. Switzerland, Iceland and Norway are also included.

[2] Around 2030 up to 300,000 direct jobs in Europe could be connected only with battery (materials, cells to pack, EV) manufacturing. Beyond 2030, these numbers could at least triple. Taking into account also the downstream value chain including battery-based products and a future circular battery economy the direct and indirect job might be on a level of up to several million in the long-term future.

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will be needed in the next 5-10 years and beyond at the European level and accordingly a much larger number of employees will need to be re- and up-skilled[2].

Hence, it is urgent to understand the demand for workforce and required qualifications arising across Europe: along the value chain, across the Member States, in companies, by number, as well as by qualification profiles. Core technical knowledge/skills, wider technical knowledge, and transferrable skills are of high importance. The development and expansion of different educational segments must be rapidly invested in and implemented, including Academic, Professional, Vocational and Public/User segments along with measures that stimulate gender balance in all areas.

Key points to highlight the importance of innovative education in battery field:

Addressing Rapid Technological Advancements: battery technology is evolving at a rapid pace with advancements in materials, design, and energy storage capabilities. It is essential to consider the latest developments and technologies to update the programmes and subjects/topics taught in all years.

Interdisciplinary Approach: it is essential to bridge the gap between various scientific and engineering disciplines as battery technology involves chemistry, physics, materials science, and mechanical and electrical engineering.

Research and Development Opportunities: high level education provides students opportunities to engage in research and development projects related to battery technology, to encouraging experts to look for, new relevant innovations.

Sustainability: discussions on sustainability, recycling, environmental impacts, responsible research and development practices, are part of the new curricula, addressing global challenges, such as transitioning to clean energy.

Laboratory Work and Experiments: practical, hands-on experience is fundamental in battery technology. It is crucial to conduct hands-on experiments and gain practical insights into new battery technology starting from cell production. These aspects should involve all levels from vocational training to PhD students.

Collaboration with Industry: collaboration between educational institutions and industry partners is facilitated through innovative training relevant to industry needs.

Promoting Entrepreneurship: innovative education can foster an entrepreneurial spirit, encouraging students to explore start-ups and innovative business models.

Influence on Policy and Regulation: work in education in this field should inform the development of policies and regulations related to battery technology.

1.1 Scope of the document

This Position Paper is a high-level document illustrating the joint view of the cross-cutting Task Forces, operated jointly by Batteries Europe and BEPA, on the topic of Education and Skills. The identification of the topics analysed and addressed was performed with input from relevant EU stakeholders. The main purpose of this Position Paper is to identify the current skill gaps and educational needs for different educational segments and across the Battery Value Chain (Figure 1) while considering the capacities for education and existing programs and measures on respective aspects. The educational segments considered are Academic, Professional, Vocational, and Public/User. Proper measures should be done to stimulate gender balance in all areas of education.

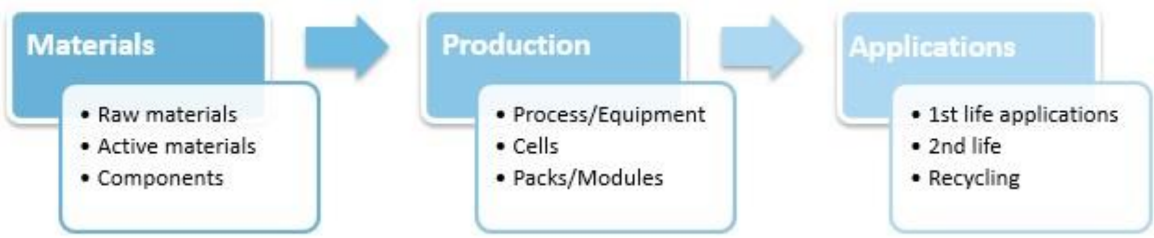

Figure 1: Battery Value Chain (simplified) as considered for the analysis in this position paper

Besides scanning the literature and projects running on this topic, inputs were received by the Working Groups in the form of an open consultation. Lastly, based on the analysis and projections, recommendations are made for the next 5 - 10 years and beyond. This Position Paper focuses primarily on Lithium-Ion Batteries (LIB) as LIB will be the dominating battery technology in the next decade, but we also anticipate a strong rise of Sodium-Ion Batteries as similar skills can be assumed. Further, skills related to other battery technology (e.g. lead acid, redox-flow batteries or any other type of batteries) are not excluded, whenever similar types of skills are required. Innovative education is a driving force behind advancements in battery technology, as it equips students with knowledge and skills, and it is required to push the boundaries of what is possible in this critical field. It ensures that future workers, at all levels, are well-prepared to make significant contributions to materials production, manufacturing, recycling and improvement of workforces in the entire value chain in a rapidly changing world, so helping Europe to compete with the great world powers in this sector.

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2 STATE OF THE ART 2020 – 2030

This brief on the State of Art of Education and Training for the European Battery Value-Chain focuses on the period 2020-2023. The position paper from Batteries Europe in 2020[7], stated that a competitive and innovative battery sector requires a properly educated and trained workforce, and that knowledge and skills gaps were challenging, and the establishing of an education and training infrastructure was in its early stages. This updated review focuses on developments in the area including issues such as the impact of the Covid-19 pandemic, volatile energy prices, political shifts and changes in national and EU battery funding. This section also highlights the ongoing work on skills identification and progress and areas that continue to need development in national education and learning infrastructures aimed at addressing the needs of battery education.

2.1 New factors

Since 2020, some new and unforeseen factors have affected the development of education and training offerings in the field of battery technology. These include:

The Covid-19 pandemic (2020-2022) developed a readiness for more flexible (e.g. including virtual) education but also temporarily slowed down development of needed new education and training programmes.

Volatile energy prices and a problematic raw materials market halted the rollout of planned battery gigafactories. This, in turn, slowed down the start of regional vocational education for these plants.

The US Biden administration's Inflation Reduction Act (IRA) caused the re-direction of some European battery value-chain investments to the American continent. Education and training development in European regions where investment is cancelled are thereby highly affected.

Recent real and potential future cuts in national and EU battery funding[8,9] in addition may cause uncertainties and slow down or stop educational and training developments in the most critical stage of the transition to a battery economy.

2.2 Skill Card work

The consciousness about recruitment needs in the battery industry, new occupations, new skills and skills in high demand has developed considerably since 2020. Recruiting gigafactories have since defined better what they need and also gained some initial experience. The ERASMUS+ ALBATTS project[10] and EIT InnoEnergy Skills Institute have shared empirical findings and analyses and presented dozens of new occupations and skills, which are also being discussed with ESCO (The European database of Competences, Occupations and Skills), with the intent of inclusion in their database. This work benefits the education sector, HR (Human Resources) professionals and national education projects.

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2.3 National education development / learning infrastructures

National member countries' development of both the Battery Value Chain and education structures has developed considerably. National or regional education development projects and initiatives are proceeding in a number of states, such as Norway[11], France[12,13] and Germany[14,15]. Research investments are sometimes combined with training and competence centres, sometimes integrated or including pilot manufacturing lines[16].

2.4 National education development / learning infrastructures

From 2020 onwards, some re-evaluations are ongoing:

White vs Blue-collar staff: In 2020, the main focus was on education needed for specialised and general engineers and managers for the battery industry, which is pivotal for starting new production. Then as more gigafactories were starting up, a considerable need of qualified vocational workers emerged which, for example, constitutes about 80-90% of the battery cell production workforce at Northvolt Ett in Skellefteå, Sweden.

Upskilling/reskilling vs basic initial education: The initial emphasis on upskilling and reskilling of professionals with existing and relevant competence and experience is still strong, but it is becoming increasingly clear that there must be considerable recruitment of young people, coming directly from customised initial education. The development of the basic education structure for initial education, both vocational and academic, is lagging in European regions due to planning routines and long lead times for young people to go through a long education programme.

Diversity in the workforce: In European-owned industrial battery projects there is a strong emphasis on recruiting women for all tasks on all levels. This has shown to be possible. Northvolt, for example, now has about 29% women employed, aiming at a 50/50 distribution[17]. It is furthermore clear that recruitment to European battery gigafactories is done over the whole of Europe and also internationally with an immigrant workforce moving to Europe. Recruitment is presently focused on finding the right expertise with relevant experience and finding trainable people in a shorter time perspective.

Focus on battery cells or industrial methods: The first reaction of education providers to the needs of the Battery Value Chain has often been to concentrate on the batteries themselves. However, when industries are consulted, the blue-collar workforce needs mostly education and training in modern industrial ways of working, aimed at Industry 4.0 (smart manufacturing and the creation of intelligent factories)[18]; digitalisation, problem solving, cross-disciplinary and soft skills, etc. It is the workforce recruited for their existing skills in other industries, often engineers and technicians, which are prioritised for a deeper knowledge of batteries, as a new application area for their existing skills.

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2.5 Development in educational segments

2.5.1 Academic undergraduate level (EQF6)

We have not yet seen clear examples of undergraduate (bachelor level) education programmes aimed at the battery industry in particular. However, many existing undergraduate academic engineering profiles, such as electrochemistry, material engineering, machine and electrical engineering etc, constitute a good foundation for work in the battery industry. At some universities, there are courses at the undergraduate level available for interested students, but these kinds of courses are still not often optional elective courses within relevant standard programmes. An example of such a course is "Batteries for Electromobility" at Uppsala University, a flexible ordinary university course at bachelor's level.

2.5.2 Master's level (EQF7)

Master's level education is the strongest education area developed directly for the battery sector. Some examples are the following European Masters programs of which all but MESC are new since 2020:

- MESC – Erasmus Master program, *a* 2-year energy storage programme at five universities: *Amiens, Toulouse, Warsaw, Bilbao, and Ljubljana*
- Uppsala University, *Sweden*
- Chalmers University, Sweden
- University of Bayreuth, Germany
- Politecnico di Torino, Italy
- Berlin University of Applied Science, Germany

2.5.3 PhD education level (EQF 8)

EU mechanisms, as well as private and national public funding (including IPCEI on Batteries & EuBatin), offer possibilities for partners' doctoral programmes, which have increased considerably. The EU mechanisms include the ninth Framework programme (Horizon Europe), Marie-Sklodowska-Curie Networks European Training Networks (ETN) like Polystorage, Marie Skłodowska-Curie Actions (MSCA) COFUND projects like Destiny, other H2020 projects, Alistore-ERI co-shared Ph.D. program, etc.) which can provide highly skilled future development engineers, managers, researchers, and professors, but still in limited numbers. All doctoral programs allow high mobility and secondments at different universities, industrial partners, and knowledge institutions. These enable students to obtain broader knowledge and additional working experience, due to hands-on practical work in different laboratories.

2.5.4 Vocational Education: IVET & CVET (EQF 3-5)

Vocational Education and Training is a crucial area for development. IVET (Initial Vocational Education) in EU member and associated countries does not yet have the national suitable and relevant course plans for public education available, but where there are industrial needs, solutions are developed, like

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education for Northvolt's gigafactory in Skellefteå, Sweden. CVET, Continuing Vocational Education, is upskilling and reskilling the workforce with existing knowledge and skills, for both established jobs and new jobs in the sector. CVET has many providers, private and public. InnoEnergy Skills Institute (formerly EBA Academy) offers courses in most countries, tasked by the European Commission. Both IVET and CVET can be started with short lead times, but actual jobs to apply for must be locally available after the education and training to motivate individuals to participate.

2.5.5 Upskilling/reskilling

An area of upskilling and reskilling that individuals with existing relevant competences and experience often need is battery- and energy-storage-specifics. This training can allow them to apply their existing skills to a new area. They also often need new skills, and further training on existing skills. Those individuals often make use of VET offers (e.g. private virtual and physical trainings as mentioned above). This is now proceeding well, with the help of national and regional education providers, both public and private, and with transnational initiatives such as:

1) InnoEnergy Skills Institute (EBA Academy), being represented directly and with partners in most European countries, offering a wide range of up- and reskilling options.

2) The Pact-for-Skills initiative which is primarily represented by the Automotive Skills Alliance, ASA. Pact for Skills works with sectoral alliances of industry, the educational sector, the social sector, EC regions to establish up-and reskilling solutions and fund them.

3) Battery MBA - which is a leadership training programme in the sector.

However, with the absence of tailored educational trainings (by topic, size, format) the industry had to develop in-house trainings in the past years. For larger companies in this posed less problems as for SME with less resources to develop own solutions. Thus, the broader availability of up-/reskilling measures and trainings as well as the broader roll-out and through-put needs to be addressed in the coming years.

2.5.6 Autonomous learning

There are always individuals who learn on their own out of general curiosity or interest and for their own upskilling/reskilling in preparation for new job possibilities. The possibilities to do this have increased, but it is also important to get recognition and certification of the learning, especially if it is in preparation for a new job. Development work in the sector of micro-learning with badges or other recognition is ongoing, and, for example, integrated in the ALBATTS courses hosted by the ASA free course offerings. There are also many MOOC courses on battery technology on different platforms available both for free and with a paid certificate, for example, "Batteries: Powering a Mobile World" on the learning platform "Learning for Professionals". In addition, there are some relevant "micro-master" / "nanodegree" / "specialisation" course packages available in many upskilling / reskilling

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subjects, but a specialisation MOOC course package on batteries and energy storage, or on battery cell manufacturing, is still lacking.

2.5.7 Increasing volume and scale of educational offerings

As shown above, there are good examples of education development programmes and projects, and education and training possibilities in different European and associated countries. However, examples are not sufficient, educational training and programs need to ramp-up by number of offers and by through-put of people. European universities have a strong link between research and education: they can offer only what they also research. This is concerning, since relatively few European universities have sufficient battery research to also offer qualified education. Universities in regions where battery-industrial activities are ongoing or planned do also need to establish needed education in their regions, and they need to do it now. European universities do seldom sub-contract one another for delivering needed courses, but this could be an option, well in line with policies of the EHEA. We have an urgent climate-crisis which motivates new and bold solutions.

2.6 Conclusion

Engagement in developing education and training solutions and infrastructure has visibly increased on both the European and national levels. Since 2020 many good benchmarking examples have appeared but are not yet up to the projected needed volumes. Especially the academic sector’s undergraduate program level is lagging behind, probably due to lack of local battery research at universities, and thereby no traditional way to train teachers. This can be addressed through collaboration between universities. The education and training for new green skills must proceed faster, and non-traditional steps are required.

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3 FUTURE SKILL NEEDS TOWARDS 2030

The battery industry needs differ **along the Battery Value Circle**. With increasing battery use, other stakeholders and the public need to be educated. A cross-disciplinary approach is recommended to create many highly educated and qualified academics, technicians, engineers, managers, consultants, entrepreneurs, and policy makers. This will call for increasing capacities within existing education platforms and the creation of new specialised courses and programs, which will assist in filling existing vacancies in the value circle and in other related areas. Education should cover seven main elements (Figure 2): Science & Technology; Integration & Applications; Circular Economy; Processing & Manufacturing; Logistics & Safety; Digitalization, and Social Impact.

Additionally, various cross-cutting soft skills should be a complementary part of the training programs.

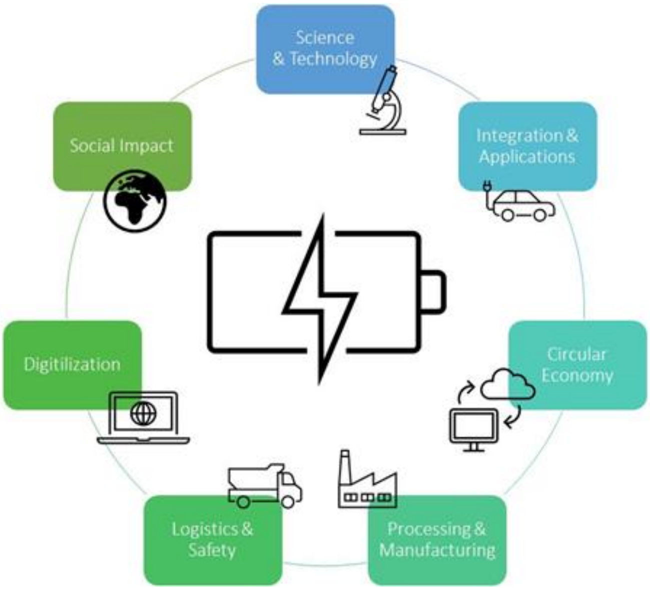

Figure 2: Main elements of battery-related education

Education and knowledge in battery components and production require accelerated efforts. A scaled battery production and ecosystem also needs a scaled workforce. A particular challenge is to increase the workforce and collective knowledge on large-scale battery production. This can be achieved by **professional education** incorporating the above main elements, and by **vocational training** for the specific work within the Battery Value Circle.

Re-skilling of the workforce from current ICE value chains but also from other matching process industries is currently regarded as a necessity for most of the qualification profiles required to enable large-scale manufacturing for cell production. In this context, **design-to-cost** and **design-to-manufacturing** aspects are of key importance. Moreover, continuous re-skilling demands for upgrading and/or renovation of production lines for future battery types and other needs must be addressed. Close synergies between companies and academia are seen as essential to achieving this continuous education.

The **product integration** on system-level requires significant skills development (e.g. engineers with more applied skills in construction and design at Bachelor and Master levels). For example, in the

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automotive industry, it is challenging to reskill employees with a mechanical background to electrical applications or to find sufficient personnel e.g. with professional education in the field.

Knowledge and skills in the actual **use phase** of the batteries, their functioning principle, and for second life of batteries will become increasingly important in the future. Operating used batteries and re-installing them for a second-use application requires a workforce with proper knowledge about ageing processes in connection with **safety**. Safety is thus a priority issue for all stakeholders throughout the entire battery lifetime and utilization. Knowledge of **battery recycling** (e.g. proper disposal, recycling options, etc.) and cross-cutting topics such as **environmental aspects, digitalisation, business models**, and **circular economy**, are increasingly important across the value circle.

Consequently, concrete actions are required in **academic education** to build up a trained workforce for the future battery industry with expertise along the Battery Value Chain in the next years. Academia should provide attractive specialised academic education programs for young students. Programs should build curricula based on interdisciplinary educational areas, with some key areas listed below for students of different disciplines:

Science & Technology: Materials science and engineering/ Electrochemistry and characterisation/ New and emerging battery materials & technologies/ Cell manufacturing /Battery testing.

Integration & Applications: Module and pack assembly including Battery Management Systems (BMS)/ Battery control and system integration/ Battery applications.

Processing & Manufacturing: Process engineering / Engineering and cell design/ Design of equipment and battery manufacturing/ quality control & testing.

Circular Economy: Re-use and Recycling/ Raw materials extraction and processing/ Design for Recycling.

Logistics & Safety: Handling and transport of batteries/ safety standards and tests/ insurance.

Digitalization: Data handling, processing and management/ artificial intelligence/ robot co-working.

Social Impact: Social sciences and Economics (related to battery manufacturing and use).

Different funding schemes and measures (e.g. EU wide pilot lines [19,20] Just Transition Fund (JTF) sources[21], Recovery and Resilience Facility funds[22], the Forschungsfabrik Batteriezellen FFB in Germany [23], the CoLabs in Portugal etc.[24]) are only a few possible initiatives which should support educational training and courses with providing access to their infrastructure (e.g. demonstrators). Graduates should have a possibility to gain practical experience and skills, for example, on battery manufacturing. It is important to develop specific courses and master programmes' curricula on specific subjects relevant to battery industries since many trained personnel (e.g. operators, technicians, process engineers, maintenance engineers with respect to the battery/cell manufacturing industry as well as electrical drive technology) will be required around production sites (who are trained either to a Master's or Doctoral level). In addition, a close connection with companies and application-oriented R&D is necessary to enable early practical work experience, and the promotion of specific internships in companies to ensure a balance between theoretical and practical knowledge. In this respect, Battery2030+ coordination and support action (CSA) includes a Work Package dedicated to developing European curricula in future battery technologies (WP4 of Battery2030+ is participated by POLITO, Uppsala University, CEA, CNRS, CIDETEC, CIC Energigune, KIT, NIC, DTU, VUB, MEET, WUT, AIT, TU DELFT, Aalto, NTU, and SINTEF).

Professional education is essential to have highly qualified professionals in battery production, system integration of battery-based products, and monitoring, collecting, and recycling. Educational measures should be developed and implemented jointly by training providers focused on training in the workforce collaborating with industrial partners, to reduce time, effort, and financial resources for industries on training new employees. Facilities for practical hands-on training should be established and existing facilities such as pilot lines and FFB should be used. There is a strong urgency to organise practical training sessions for trainers on pilot lines designed for educational purposes and realise specific centres spread in different geographic sites in Europe for this scope. These centres can provide education for academies, where the availability of pilot lines is reduced, but also for companies on demand, to skill and reskill their workers. This can speed up the process to educate a larger number of workers and researchers.

Two important cross-cutting needs appearing along the value chain from the raw materials to production, applications, and recycling are digital skills and a digital mindset, as well as holistic battery system understanding. All main elements (Figure 2) should be considered for professional education. With respect to large and complex projects and large-scale production facilities, there is a special need for highly experienced battery experts in upper management. They should be able to understand the technical aspects and at the same time make decisions on strategies, investment, etc.

Vocational training is critical for specific areas of the Battery Value Chain, especially with regards to increasing manufacturing capacities, where 80-90% of production employees are blue-collar workers. Special attention should be given to education on handling and transport of batteries, their installation, and testing with emphasis on safety. Such training can be offered to people with solid industrial understanding and interest in batteries, battery technology and production.

Acceleration in technology transfer is needed for all educational segments and all battery-related topics including the education of the **wider public** and of various stakeholders such as **policymakers**. For example, acceptance from the public/user is an important contribution to the opening of markets and removing barriers to the uptake of batteries/EVs. As today's awareness of the advantages of using batteries is low and concerns about safety issues are high, the wider public should be properly educated about all aspects of battery technologies, their maintenance and proper use. The predominant focus should be on generations of kids and young adults.

To achieve the above large-scale accelerated training programs, there is also a **gap in available trainers and education personnel**. Thus, besides specific **train-the-trainers programmes**, innovative approaches to this challenge need to be taken. As an example, cascade education is recommended where young students themselves educate kids in school.

To summarize the key future needs:

- The accelerated roll-out of training (reaching a large number of trainees, e.g. via virtual formats accompanied by physical hands-on training; incl. training the trainers); the period from now until 2030 is critical as we are in a strong take-off in the S-curve.

- Increased focus on vocational training and re-skilling of workforce thus also gaining experience in process scaling to achieve cross-industry transfer from other sectors to the battery sector.

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Research and Innovation Programme under Grant Agreement N. 101069676

- Address circularity, critical raw materials, SSbD principles in the curricula to support Green Deal policies.

- Further educational outreach to public/end-users, elementary schools and other stakeholders is required to implement battery knowledge and thus acceptance amongst wider public and specific stakeholder groups and to sow seeds for next generation scientists and workers.

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4 GAPS AND CHALLENGES

To respond to the worldwide increase in utilisation of batteries and battery-based applications, there is to-date already a critical need for schooling at all educational levels and to train a skilled workforce, and to do this throughout the value chain. A recent report from the IEA shows that there is a significant need for workers in the battery sector at various levels[25] There are clearly identifiable gaps between the actual situation and an ideal and even an acceptable education and training level, and this is in several areas as is reflected in the diagram below:

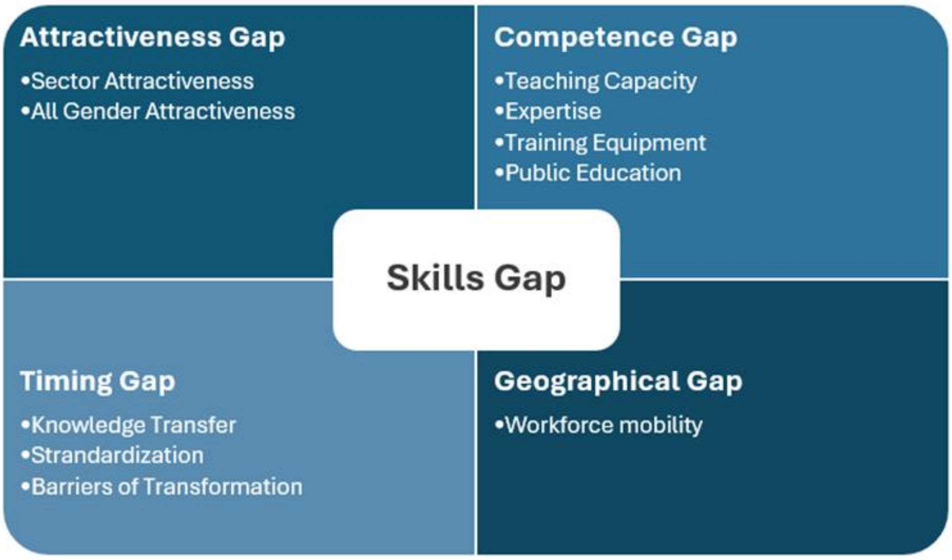

Figure 3: Four major areas concerning Skills Gaps[26]

In the remainder of this chapter, we focus on several elements from the model in the image, including the following. Most of the other themes included in the diagram are covered elsewhere in the paper.

- Expertise
- Workforce Mobility
- Standardization
- Barriers of Transformation
- Training Equipment

These gaps - very much linked to each other - create several challenges, which can be overcome with adequate countermeasures.

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4.1 Expertise

Competences in large-scale cell manufacturing are currently limited despite the new investments in battery cell manufacturing in the EU[27,28].

While the expertise of the various areas of the batteries value chain is available and well developed, it is dispersed through different graduate schools, universities and research organisations. The level of educational development differs between Member States, but they all suffer from limited teaching capacity.

To address this, The European Commission could allow for Calls for proposals to improve on required competences. Existing programs from universities, institutions and research centres can be used as stepping stones to ensure successful new training programs and learning paths for each function.

There is an opportunity to train workers over the age of 40, to acquire skills needed to start a new career in the battery sector. This will help to reduce long-term unemployment. Specific courses aimed at these people should consider that they already have work experience[29].

Also crucial to the success and/or training or a future workforce in the battery sector encompassing the whole Battery Value Chain is the need to develop strong capacity in training and teaching with adequate technical, scientific and pedagogic competences. Some of the gaps and challenges that need to be addressed in this area are[30]:

- Developing specific training and support materials to train the trainers, considering the target audience and level of expertise.
- Guaranteeing that the trainers acquire the required competences needed to efficiently transfer and evaluate acquisition of knowledge.
- Ensuring that the trainer's expertise and competences are renewed regularly in line with the evolution of scientific and technical knowledge in the battery sector, and the changes required specific to their geographic areas.
- Identify scientific and technical areas in which trainers are needed with the input of all relevant stakeholders, especially industry.
- Focus on boosting the attractiveness of the battery sector for future trainers.

4.2 Workforce mobility

Existing programs attract students from other parts of the world and therefore it is important to make it attractive for European students too. The EU could subsidise graduate schools & universities to allow for permanent and targeted communication[31].

In addition, to ensure that mobility is no longer a limiting factor, students in each Member State ought to be able to follow studies in batteries' faculties in the different areas of battery expertise, from development of batteries to final disposal at end-of-life[32].

In order to better understand what types of communication, we can monitor specific indicators. Examples of these indicators include the actual types of educational programs, the number of students enrolled for each programme, per annum and the distribution of these students across Member States. This approach will allow for more targeted and effective communication.

Interdisciplinarity/multidisciplinary research and value chain-based training could increase the skilled workforce and remove barriers between different specialists to favour exchange of knowledge and competence between the various actors involved in the education/training sector.

4.3 Standardisation

The level of education is quite different between graduate schools, universities, research centres and even between EU Member States. Standardisation requirements in battery education are needed. The purpose should be to ensure compatibility amongst battery faculty education between educational institutions and Member States.

A barrier to overcome are the existing differences in approach between industry, academia, and training schools/centres. They have different goals and targets, due to competing interests with respect to knowledge transfer, intellectual property issues, confidentiality, and sensitive information. As a result, the specialised knowledge & expertise tend to remain internal to the company/industry. This can further complicate the development of joint educational measures between academia, training centres and industry.

Standardised and specific curricula at bachelor's and master's level for different areas of the value chain could be a valuable solution, to support early-career researchers, whilst basic STEM skills are still of significant importance. STEM skills are still essential for early-career researchers, as they are important to equip them with the critical thinking, problem-solving, and technical abilities needed to succeed in a dynamic research environment.

To identify solutions for standardisation of education it would be helpful to indicate which institutions provide battery specialisation, the so-called 'battery hotspots'6 to analyse the situation by setting up working groups amongst graduate schools and universities in each Member State, to request verification bodies (for example, The European Quality Accreditation Commission) to assess annually the quality of education and the level of competence of trained personnel.

The public and private sectors should increase and consolidate their efforts in identifying future needs and defining adequate recommendations and incentives to the various stakeholders involved.

4.4 Barriers of transformation

University rectors and deans need to change the current lengthy and laborious process of approving new curricula. There is reluctance of curricula defining bodies, from authorities, to adapt curriculum for middle education and vocational training, and from university departments for higher education levels. To identify curricula for battery education and skills training up to an acceptable level, a strategy should be implemented to alleviate the challenges with this process of curricula approval. Academia should recognise this situation and together discuss solutions to resolve the existing barriers. They should agree on a process to allow for a dedicated battery faculty. The public and private sectors together could support such initiatives.

On the industrial level, the challenges remain for the industrial permitting procedure which hinders the go-to-market time for battery material facilities. These slow processes could delay training as companies are reluctant to spend on training in the face of uncertainty of their facilities receiving full approval. Therefore, rapid upskilling solutions are needed for workers.

4.5 Training equipment

There seems to be a considerable lack of equipment and training labs where students would be able to carry out real-life, hands-on experiments, to complement the theoretical studies, hence acquiring a more complete knowledge and competency level2. The challenge is how to create interdisciplinary research curricula strongly connected with education through the entire Battery Value Chain. These curricula would then form a foundation that these training facilities could be built on.

An evaluation of the current situation on available training equipment in each Member State should be done to identify which kinds of investments are needed[31]. Such an approach would lead to a much smaller separation between industry/practical utilisation and academia, which is of the highest importance in this field. Building up pilot lines, demonstration, and training centres, etc., renewing old laboratory equipment, and allowing young students to access public and private production facilities will be crucial in the next few years. Facilities for research at Technology Readiness Levels (TRL) 5 – 6, or training facilities for vocational training at TRL 9 should be prioritised over facilities for research at TRL 2 – 3. The use of digital tools and virtual reality in training courses can help to improve the skills and knowledge transfer. This will also increase time flexibility which is a critical aspect when training is aimed at active workers.

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5 TRAIN THE TRAINERS/TEACHERS

5.1 The importance of skilled trainers for the battery sector

A functioning training and knowledge/competence transfer strategy has several interconnected parts. Trainers/teachers/mentors are a fundamental part of this system. The way they approach teaching is key to ensuring they successfully transfer knowledge and skills to their trainees/mentees/students. In addition to knowledge transfer, they are also responsible for evaluating and identifying training needs, normally in cooperation with companies and/or training organisations.

Besides being specialists in the scientific and technical areas, they need to possess other skills to adequately perform in their roles. Some of the most important ones involve pedagogic and presentation competences, which include but are not limited to, knowledge transfer, evaluation, development of teaching materials suited to the training purpose and training and presentation skills. At the European level, usually, those competences are taught and developed in specific training courses, either at the vocational or university levels. Normally the knowledge and expertise are taught in a generic way or aiming to train teachers of the elementary or medium formal education levels, not fitting the specific needs of any particular industrial sector. In many situations, as is the case for most university professors, no specific training occurs, and those skills are acquired by practice, an inefficient strategy as it may take too long and may lead to the acquisition of poor teaching practices.

As there is a strong need for skilled workers in all parts of the Battery Value Chain, there is also a strong need for trainers with knowledge and expertise in the sector. This is recognized by the EIT Raw Material report "Future Expert Needs in the Battery Sector"[2] which considers that "train the trainers" should consider the entire value chain and should be evolved to specific programmes.

Normally trainers are recruited/selected considering their expertise and experience in the battery sector, and previous experience of being a trainer. Pedagogical knowledge and skills to, for example, develop teaching materials or evaluate knowledge acquisition, are not normally considered vital to trainers, unless imposed by legislation or companies requiring trainers that be certified with these skills. This state of affairs is particularly seen in teaching at university level, where professors must also be researchers and are normally selected based on their research activities and results, not on their teaching capacities. These issues may limit the effectiveness of existing or future training activities in the battery sector. This, in turn, may limit the sector's future competitiveness and overall sustainability.

Presently there are some "train the trainer" initiatives in the European Union. The following non-exhaustive list offers examples of these training offerings, mostly delivered online:

- The ALBATTS (https://www.project-albatts.eu/) project has published 'A Handbook of Battery Teaching'. This is aimed primarily at vocational teachers.

- The European Battery Alliance Academy, which while focusing on the training and retraining of workers, also has some activities in training the trainers and course and competences certification[33].

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- Reed Courses: A UK-based online learning platform offering a well-structured TTT diploma with certification and learning paths.

- The Open College: An Irish e-learning platform offering TTT courses with QQI (Qualification & Quality Ireland) certification. However, there is a lack of training courses aimed specifically at the battery sector. Although there is some activity in this area, for example, ALBATTS has developed guidelines for train the trainers, much remains to be done. Hence, due to the relevance of these issues, a systemic approach is needed considering the various aspects which are listed below.

5.2 Need for evaluation of the current state of Train of the Trainers

There is currently no assessment of the current state of Train the Trainer offerings in the European Union. Without this, a definition of a strategy and policies to address the existing gaps cannot be meaningfully developed. Hence, the creation of an international commission/working group is recommended. A suggested title for this group is Batteries Europe Education Commission (BEEC), under the umbrella of Batteries Europe, or other collaborative platforms such as InnoEnergy. The function would be to assess the actual situation with recommendations for a path forward. The working group should include renowned specialists and representatives from all relevant stakeholders, in particular: universities/research centres, industry, recycling industry and battery suppliers, manufacturers and retailers. The progress of the working group should be overseen by a high-level board of specialists representing different European regions. Proper funding and support should be provided to the working group to achieve its goals.

Due to the urgent need for trainers the working group should produce a final report with recommendations and financing needs to be available Q1-2025. The report should present an evaluation of the current situation, considering but not limited to the following issues:

- Number of organisations, including high schools, graduate schools, universities, and vocational training centres, which have dedicated classes or courses on themes related or of interest in the battery sector;
- Number of teachers/lecturers/trainers involved, and their education levels and training certifications.
- Number of students involved, including gender representation.
- List of existing battery education programs, courses, and specialisations.
- List of European Calls, grants, and incentives to promote the acquisition of battery-related knowledge and competences, a list of collaborations between educational institutions.
- Description of training equipment available and its location. This should be complemented with existing Transnational Access schemes for accessing research infrastructure. E.g. Stories Project. https://www.storiesproject.eu/calls
- Identifying international and national standards and guidelines specifically aimed at battery education and/or training.
- Understand the level of public awareness given to the subject.
- Renumeration of teachers: how does this compare with other disciplines?
- Which verification bodies and/or certification schemes are in place?

Based on findings, the report should define a set of actions and/or good practices to improve the current situation to acceptable levels by 2030, as there is an urgent need of trainers in this domain.

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Some issues need immediate attention to train the highest number of people in short time. First, a diagnostic should be undertaken to identify the geographic distribution of battery competences and needs. It is essential to determine the “battery hotspots” determining where to initially focus. They may correspond to regions where gigafactories will or are being built, or areas with significant generation of spent batteries. The next step would be the development and implementation of pilot projects for training trainers also in those regions, with curricula tailored to their regional needs. The results of the pilot projects, in particular guidelines and teaching/training materials, should be made public, to serve as blueprints for the development of training programs in other regions adapted to specific settings. The development of these pilot projects should be combined, whenever possible, to the development and implementation of pilot lines aimed at training workers in battery manufacturing activities. The educational curricula should focus on the practical training of trainers and maximise dissemination and range of those activities. An emphasis should be given to digital training, for example using virtual or augmented reality, as it reduces the need for the trainees to leave the workplace.

5.3 Key aspects concerning trainer certification

Training certification relevant for Europe should take into account issues that are regional for battery training and issues that are broadly applicable across Europe. For example, only in a certain number of regions are there issues related to the extraction and processing of raw materials of cell and battery assembly relevant. However, there are key issues that are the same across Europe, for example, recycling batteries. Thus, trainers should be able to develop relevant skills regardless of the countries or regions where they are working, and the curricula and/or training activities should be developed with that goal in mind. This strategy will also ensure that a pan-European training corps is created.

The development and implementation of a certification scheme valid across the European Union will ensure a uniform and fair common ground for trainers across Europe, while guaranteeing standards in the competences that trainers must have. It is also important to certify training courses that may grant ECTS (European Credit Transfer and Accumulation System) credits.

The recruitment of certified trainers also increases the attractiveness of being a trainer, as it limits the market to those who invest in obtaining the certification. This benefits the industry as it requires the trainer to fulfil certain quality criteria, hence better results are expected from training activities. This certification should be renewed periodically, for example every five years, to ensure a renewal of skills in the battery sector, and to take into account the natural evolution of scientific and technological knowledge.

The BEEC should also be responsible for the definition of the certification scheme, in particular the requirements for certification or renewal of certification. The BEEC should upgrade the certification scheme periodically, considering not only the scientific and technical development in the battery sector, but also the evolution in pedagogic methods and new teaching instruments and methods. In addition, the BEEC, in collaboration with organisations at the national or regional levels (by delegation of competences for example), should take responsibility for certifying educational institutions, training centres, and research centres, among others; that may engage in training-the-trainers activities.

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5.4 Incentivising train in the trainer's initiative

Member States should encourage universities, graduate schools, training centres, professional/vocational training schools, and research centres to actively participate in and promote train the trainer activities, either by interacting with companies to address their specific training needs or by developing specific training courses. Specific funding and/or support should be provided by the Member States for training activities for the battery sector, integrated into specific support packages for the sector through competitive calls for proposals. These actions are particularly needed for university education and/or training, as universities normally respond slowly to changes in new areas and/or urgent needs from the industry, both at the regional and international levels.

5.5 The role of mentorship, tutoring and coaching

An additional method of developing training skills is mentorship, tutoring or coaching. Depending on the circumstances, specifically designed training may not be practical. For example, in the case of small companies installing battery systems, it may be a good option to transfer knowledge and competences regarding batteries through mentoring or tutoring. Coaching is also an option in larger companies. In particular, when compared to classroom training, it can be more effective, as there is a more direct relationship between trainer and trainee. However, time limitations and the unavailability of mentors and tutors can hinder the utilisation of this type of training, requiring specific funding or support for those activities.

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6 AWARENESS BY POLICY MAKERS AND GENERAL PUBLIC

6.1 Awareness by policy makers

Policy instruments can only be put into practice when there is broad understanding amongst policy makers and the public that battery skills and education is an issue that must and can be addressed.

To accelerate the implementation of educational and training programmes in the European battery sector, policy makers need to be aware of the policy actions that they can undertake and what the possible impact of these policies is. This chapter outlines several policy actions that could be taken on a European, national and regional level. Most actions will likely be suited to a regional level.

The strategies proposed for action at various levels—European, Member State, and Regional—aim to foster the development and utilisation of battery-related knowledge, skills, and infrastructure.

At the European level, initiatives focus on bolstering research and development infrastructure by encouraging cross-disciplinary knowledge transfer and supporting joint industry-academia programs. Additionally, advocating for curriculum standardisation across the EU, particularly in battery production, usage, and recycling is a priority. Efforts should concentrate on enhancing industry engagement by identifying needs and fostering researcher mobility through funding opportunities.

Furthermore, initiatives aim to enhance the attractiveness of the sector by stimulating collaborative efforts among early-career researchers and disseminating success stories and best practices via platforms at both national and regional levels.

At the Member State level, the emphasis is on developing vocational[34] programs tied to emerging battery facilities, including internships with dedicated funding. Continued analysis of necessary skills, alignment with industry requirements, and curriculum adaptation based on EU-wide standards, conform to Net Zero Industry Act[35], constitute key elements. Establishing learning labs, promoting diverse teaching methods, and fostering industry collaboration for standardised qualification programs are recommended strategies at this level.

At the Regional level, strategies focus on tailoring qualification programs to local industry needs while aligning with broader EU standards where possible. Moreover, the focus is on flexible learning methods, digital tool integration, and the establishment of regional educational networks concentrating on the Battery Value Chain. Additionally, creating validated pathways for career development, collaborative models between local industry and schools, and continuous training for educators are seen as crucial strategies.

The list above is non-exhaustive but could be used to help public officials at the various levels to find a set of policy initiatives that they can start, or join, to ensure that Europe has the workforce to realise the ambitions of the battery sector.

6.2 Awareness of the general public

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Public education on the positive impacts of batteries is instrumental in making the field more attractive for students and encouraging the re-skilling of workers[2]. By effectively communicating the significance of batteries in advancing sustainable technologies, addressing climate change, and driving innovation, public perception can shift positively. A well-informed public is more likely to recognise the crucial role batteries play in renewable energy storage, electric transportation, and overall environmental sustainability. This awareness can, in turn, inspire students to pursue careers in the battery industry and motivate workers to acquire new skills in this evolving field. While train the trainer, as mentioned in the previous chapter, will be useful, it is not enough, as many decisions about future careers or changes are taken at the dinner table and discussed with parents, partners, friends and family. As (future) employees will embark more on a trajectory of life-long learning, it is important that this happens in a wider society which embraces the battery sector as a net good for Europe which provides interesting and well-paying jobs.

To achieve this, the European Union can undertake the following tasks: launch comprehensive awareness campaigns emphasising the societal benefits of batteries, collaborate with educational institutions to integrate battery-related content into school curricula already at a young age, establish public learning labs to provide hands-on experiences, and offer grants to support initiatives that promote the positive aspects of battery technologies. Additionally, fostering partnerships with industry stakeholders for outreach programs and developing EU-wide standards for educational content can contribute to a more informed and motivated workforce in the battery sector.

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7 CONCLUSION

To conclude, several actions must be taken in the next few years to educate an increasing number of people with qualification profiles tailored to the industry's needs along the value chain. With proper coordination between individual Member States and by expanding current programmes the impact can be swift. To implement and coordinate all actions and skills and education level, coordination and support actions would be required to homogenise activities at all levels in various places. Subsequent actions for the broader roll-out will have to follow in the years after 2025.

7.1 Short-term recommendations: <2027

Prioritise funding on Education: EC should prioritise incentives for universities to cooperate more in education with main stakeholders to speed up the skilling and reskilling process which is urgent.

Skill Development: Urgent action is needed to bridge skill gaps and create a competitive workforce for the evolving battery industry through targeted training programs, education initiatives, and strategic partnerships.

Cross-disciplinary Education: Launch specialised courses urgently to address skill gaps in the entire Battery Value Chain.

Re-skilling Workforce: Prioritise re-skilling current industry workers, aligning their expertise with the demands of battery production.

Workforce Training: Emphasise rapid education and training to build a skilled workforce, boosting competitiveness globally.

Student Engagement: Implement mechanisms to attract students to battery-related subjects before their academic studies.

Vocational Training and Perception Change: Increase the attractiveness of the battery industry by prioritising vocational training and changing public awareness.

Focus on Vocational Training: Increase emphasis on vocational training, stressing experience in process scaling and cross-industry knowledge transfer.

Attractive Enhancement: Transform the perception of battery production into an opportunity, attracting local talent to strengthen the workforce.

Educational Standardisation and Public Awareness: Standardise education for researchers and bridge disparities and simultaneously educating the public on batteries for a sustainable future.

Standardise Curricula: Implement standardised Master-level curricula across Member States, supporting early-career researchers and addressing educational disparities.

Sustainable Future Education: Prioritise public education on the crucial role of batteries in building a sustainable future.

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Wider Educational Reach (both a priority in the short and long term): Expand the reach of education beyond academia to encompass the wider public, policymakers, and end-users, fostering awareness and acceptance of battery technologies.

Training and Education providers' Collaboration: Enhance practical skills through hands-on training, develop effective pedagogical methods, and foster collaboration for comprehensive workforce development through targeted initiatives and industrial partnerships.

Hands-on Training: Organise, with urgency, practical training sessions for trainers on pilot lines designed for educational purposes and realise specific centres spread in different geographic sites in Europe for this scope. Virtual Reality can be used to provide simulated experiences while there are not enough available pilot lines available.

Pedagogical Skills: Provide pedagogical training sessions for trainers, focusing on effective teaching methods and student engagement strategies.

University Engagement: Promote active participation of universities graduate schools and professional schools in tailored training activities, fostering collaborations with companies for dedicated course development.

Sense of Urgency: Today there is a serious lack of competent experts, and a significant gap for skilled technicians and engineers. These skills are much needed in many sectors in Europe, creating significant competition. This makes the urgency in the batteries domain even more apparent. An urgency aimed at every level of education to step up the efforts for enrolment, to start new and up-to-date courses, to find the lecturers to lead these programs, and to provide the necessary teaching infrastructure and equipment. At the same time, it must be highlighted that a close collaboration, hand-in-hand, between the education channels and the industry/business channels is desperately required. A more customised and cooperative type of education, stimulated by means of EU incentives, together with some kind of European curriculum for national adaption will help to close the gap for available skilled personnel in the marketplace.

7.2 Medium-term recommendations: 2027-2030

Workforces reskill: Scale up educational programs and create strong partnerships between academia and industry to meet the growing workforce demand with practical education experiences.

Workforce for Production: Expand educational programs proportionally to meet the growing demand for a larger workforce in the battery industry.

Holistic Education and Early Engagement: Prioritise holistic education with soft skills integration and engage students early on to prepare them for the dynamic demands of the battery industry.

Holistic Approach to Education: integration of cross-cutting transversal skills within training programs to effectively meet industry needs.

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Continuous Development and Certification System: Invest in continuous train the trainer programs and implement certification systems through workshops, seminars, and industry collaboration.

Guidelines for Training: Develop comprehensive courses or guidelines, like MOOCs, ensuring proper formation for training trainers in the battery sector.

Innovative Learning Paths and Collaborative Environments: Encourage innovative learning, interdisciplinary and collaborative research to enhance the educational experience in industry.

Interdisciplinary Research: Foster interdisciplinary research closely linked with the entire Battery Value Chain.

Mobility Programs: Increase mobility opportunities for students and trainers across different universities and companies enabling also the participation in internships within battery-related industries, emphasising the importance of gaining practical experience.

Use of Existing Programs: Use existing university and innovation centre programs.

Collaborative Learning: Promote collaborative learning environments among trainers to foster the sharing of knowledge.

7.3 Long-term recommendations: >2030

Innovative Training Models and Outreach: Use innovate training methods and models while expanding outreach efforts to various audiences, ensuring widespread awareness and acceptance of battery technologies.

Innovative Education Models: Explore cascade education, where younger students educate, to bridge the gap between trainers and those receiving the training.

Wider Educational Reach (both a priority in the short and long term): Expand the reach of education beyond academia to encompass the wider public, policymakers, and end-users, fostering awareness and acceptance of battery technologies.

Rapidly scalable training methodologies such as online training or blended learning should be commonplace. The training courses should be modular so that those can be modified, added more courses or omit obsolete courses as necessary.

Adaptability and Collaboration: Prioritise adaptability, collaboration, and partnerships with industry for a dynamic and practical approach to battery technology education

Continuous Adaptation: Ensure educational curricula evolve to incorporate emerging trends, including circularity, critical raw materials, and safe, sustainable battery design principles.

Industry-Academia Collaboration: bridge existing barriers between industry, academia, and schools, promoting knowledge transfer.

Partnerships with Industry: Foster collaborations between academic and public institutions and industry experts.

Competency Building and Innovation: Focus on building competences, engaging in research, and fostering innovation, for cutting-edge battery technology education.

Competency Development: Build competences in large-scale cell manufacturing and associated areas like battery components, materials, recycling and automation.

Research Engagement: Encourage trainers to participate in research activities related to battery technology, aligning their knowledge with current trends.

Feedback Mechanisms: Establish feedback loops where trainers receive evaluations from students and peers to improve teaching methodologies.

Innovation Support: Encourage trainers to explore innovative teaching methods like flipped classrooms, MOOC, increasing the use of virtual reality and simulations for effective learning.

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Batteries Europe

Position paper

Digitalisation Task Force

April 2024

In cooperation with

BEPA
Batteries European Partnership Association

ACKNOWLEDGEMENT

Batteries Europe Secretariat is an EU-funded project that has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676.

DISCLAIMER

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This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676

Acknowledgements: We would like to thank Spyridon Pantelis (EERA) for the overall coordination of the Task Forces, Alessandro Romanello (EIT InnoEnergy) as coordinator of Batteries Europe, and the BEPA Secretariat for their support in the operation of the Task Force. Special thanks to Fatima Ahmed, Adeola Adeoti, Lucia Sardone (CLERENS), and Maria Luisa Fernandez Vanoni (EERA) for editorial support. We would also like to acknowledge the inputs and considerations from the European Commission, the Batteries Europe Secretariat and Batteries Europe Advisory Board.

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This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676

ABBREVIATIONS AND ACRONYMS

Abbreviation	Definition
AI	Artificial Intelligence
BIG	Battery Interface Genome
BMS	Battery Management System
DPP	Digital Product Passport
EV	Electric Vehicles
EOL	End-Of-Life
FAIR	Findability, Accessibility, Interoperability, Reusability
THE	High-Throughput Experimentation
ICT	Information And Communication Technology
IoT	Internet Of Things
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LIB	Lithium-Ion Battery
MAP	Materials Acceleration Platform
ML	Machine Learning
PEFCR	Product Environmental Footprint Category Rules
SoX	State Of X
SoC	State Of Charge
SoE	State Of Energy
SoH	State Of Health
SoP	State Of Power
SoS	State Of Safety

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Research and Innovation Programme under Grant Agreement N. 101069676

EXECUTIVE SUMMARY

The Batteries Europe / BEPA Task Force on Digitalisation leveraged the activities of the Batteries Europe Working Groups to define the digitalisation agenda for batteries in Europe that was included in the Batteries Strategic Research Agenda.

Digital technologies are not a direct objective but an important enabler to achieve the development of innovative new services, the so called applications or use cases, leveraging technologies like digital twins, artificial intelligence (AI) and machine learning (ML), computer-aided design (CAD), data science, advanced modelling, 5G, blockchain or the battery passport that can deliver significant measurable benefits: saving costs, increasing revenues and setting up new business models, all contributing to achieve socio-economic benefits.

The current position paper presents some of these advanced technologies that could make a difference for the batteries industry. It illustrates these innovative technologies for the battery industry in the domains of engineering & design, manufacturing, maintenance, exploitation and recycling.

The native design of the battery hardware leveraging the digital technologies and continuous monitoring and control will enable the industry to optimise the state of multiple KPIs called SoX, like State-of-Health (SoH), State-of-Charge (SoC), State-of-Energy (SoE), State-of-Power (SoP), and the innovative concept of State-of-Safety (SoS) monitoring tools in battery management systems (BMS).

In conclusion, this report summarises recommendations for the central topics addressed within this position paper. These serve as guidelines for enabling advancement in the related technology domains across the whole value chain, targeting a wide range of stakeholders (s. section 5).

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Research and Innovation Programme under Grant Agreement N. 101069676

1. INTRODUCTION

Digital technologies have been used within energy systems for decades. The energy sector was one of the early adopters of large information and communication technology systems (ICT). Already in the 1970s, electric utilities used information and communication technology to aid the management of the transmission and distribution system. Many electricity markets around the world are monitored and controlled in real-time across large customer bases and geographic areas. Likewise, oil and gas companies have a long history of using digital technologies to aid exploration and production efforts. Similarly, a variety of industries have used process controls and automation to optimise energy use. Digital technologies have long been used across transportation modes to improve safety and increase energy efficiency. It is now a must have technology for electric cars to manage their batteries, and the same stands for stationary batteries that should integrate with the assets, such as buildings, renewables and electricity networks.

Blockchain, artificial intelligence (AI), machine learning (ML) and generative AI are digital technologies that are undergoing rapid development today and have the potential to bring disruptive changes to the energy landscape. Blockchain technology presents an exciting opportunity for decentralised energy environments to enable, validate, record, and settle energy transactions in real-time. Blockchain is a distributed digital ledger built on a decentralised transaction verification system; this framework could enable peer-to-peer transactions, where neighbours transact directly with each other, and trade energy generated from their rooftop solar panels and electric vehicles through the grid. These technologies play a major role in making batteries effective with an optimal lifecycle and payback cycles.

The EU Green Deal[1] and the digitalisation of the European economy, specifically the European energy system[2], will be important new priorities of the European Commission. Moreover, by 2050, renewables' share could reach as much as 87% in the electricity mix, with wind and solar energy playing a dominant role. Cheap renewables, flexible demand and battery storage will be digitally combined to shift the European power system away from fossil fuels and nuclear power to a cleaner society around variable renewables and emissions-free energy.

This shift in the energy transition will be enabled by smart digital technologies. Digital technologies will optimise the value that battery storage systems can bring to the energy markets, thereby enabling opportunities for new energy stakeholders, creating a new generation of jobs for the circular economy, and bring Europe to the forefront of leadership in the fight against climate change.

The development of digital technologies is required to improve the industrialisation of new batteries and shorten the time to market. The design of machine learning algorithms will accelerate the discovery of materials and the development of AI-orchestrated characterisation of battery materials and battery cells. Combining computer-aided engineering tools and experimental measurements will help to understand and predict the performance of batteries.

These technologies will continue to evolve more rapidly than the time required for the transformation within the mobility, storage and battery industries.

This position paper serves as an update to the last one published in 2021[3] and focusses on recent technological aspects such as common infrastructure, data shapes and ontologies, digital twins, advanced modelling and state monitoring (SoX).

Therefore, it describes yet another step in the journey of an innovation-intense batteries industry.

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2. COMMON INFRASTRUCTURE, DATA SHAPES AND ONTOLOGIES

As a complex domain, battery research highly relies on agreed terminologies and standards. Beyond fundamental science (e.g., chemistry, physics, etc.), this was historically provided merely by verbal communications and lack of a global referenceable standards. Recent activities at national (e.g., German Battery Clusters) and European level (Battery2030+, LiPLANET, BIG-MAP) address this issue, for example by providing an interactive data space[4,5], a common knowledge base[6] and battery related ontologies[7,8]. However, to date, those initiatives have included only a small fraction of data produced by the research community. To generate a significant impact, they should be extended to a broad established framework and build a common battery knowledge graph consisting of linked and machine-readable self-descriptions of digital assets, providing domain knowledge, terminologies, tools, data shapes, etc.

To do so, it is important to acknowledge that ontologies, while being the technical foundation, will not serve as a direct interface to the general community. Instead, ontologies should be mapped onto pragmatic and real-world-reflecting data shapes, addressing both general (e. g. hierarchical description of a battery module down to materials) and specific needs within the domains (e. g. definition of a cycling procedure or electrochemical simulation input and output data). Accessibility to a growing collection of those linked data shapes can be achieved by auto-generating specific end user interface from those data shapes[9.]

By fulfilling not only data experts but also end users' needs, aligned ontologies, derived data shapes and generated interfaces are critical for upcoming data space initiatives, such as Catena-X[10], which allow them to be effectively populated with content from a large community and enable data scientists, AI and simulation experts to provide shared digital services based on shared interoperable data.

Linking explicit machine-readable knowledge with experimental data in common battery data spaces will also serve as a basis for hybrid models to consider not only statistical and physical models, but also machine-readable expert knowledge. Likewise, machine-readable and consistent knowledge in form of process and material definitions will facilitate the application of sustainability evaluation tools, such as for Life Cycle Assessment (LCA), Digital Product Passports (DPP) and chains of custody. In consequence, implementing sophisticated semantic data and knowledge infrastructure will not only enable advanced internal process management and optimization, but also compliance with external regulations without additional costs.

LCA is a standardised methodology that has become the consensual tool of choice to assess the potential environmental impacts of products and processes throughout their life cycle. Although it is standardised by ISO 14040:2006 / ISO 14044:2006 and there are product environmental footprint category rules (PEFCR) for rechargeable batteries proposed by The Advanced Rechargeable & Lithium Batteries Association (RECHARGE), many assumptions are needed and different methods can be employed to quantify the environmental impacts. These facts increase the uncertainties of the results of environmental impact and hinder the comparison between different types of products. In this sense, there is a need for higher amounts and reliable primary data to support more robust LCA studies. Moreover, PEFCR should be developed and extended, not only for the battery as a product on the system level, but also for its components and materials, e.g. data on the recycling of battery components like active materials and electrolytes. Additionally, considering a wide variety of output materials and different process technology readiness levels, a more consistent and ontology-based methodological approach should be developed for levelled comparison of the environmental impacts of different recycling processes. Furthermore, in the same way that environmental impacts are assessed using LCA methodology, economic and social impacts must also be assessed in life cycle thinking (LCT) perspectives, using the life cycle costing (LCC) and social life cycle assessment (s-LCA) methodologies[1].

However, there are still significant questions regarding available data, in particular externalities costs and social data information.

For achieving interoperability of LCA standards (e.g. process flows and material exchange definitions) with material science and process engineering standards, the following actions are recommended:

- Use of the same ontology in the LCA documents for both chemical aspects at cell level and engineering/production process domain (e.g., carbon dioxide vs. CO_2).

- Implement the digital passport[2] also for battery materials and parts within the supply chain, particularly in recycling materials. Develop a common ontology for battery passport (and digital twins) based on existing ontologies like the Battery Interface Ontology (BattINFO[11]) and Battery Value Chain Ontology (BVCO[12]).

- Development of a Life Cycle Inventory (LCI) database, or LCI datasets, specifically intended to be used in the development of LCA studies or in the creation of DPPs. To ensure the representativeness of the LCA and sustainability studies carried out based on this data, specific data transfer and storage formats must be defined, considering the information that must be provided and how it must be obtained. Moreover, specific measures should be taken to protect sensitive information, for example intellectual property or business information, using protocols such as blockchain or others created specifically for battery systems. In addition, data formats should facilitate the assessment of environmental impacts, based on existing or future product category rules (PCR) or methodologies created for DPPs. Efforts should be made to ensure that all data is open source and can be incorporated into existing or future open source LCI databases, of general nature such as the environmental footprint database[13] or tailor-made for battery systems. Future LCI databases should be updated periodically and allow for the submission of new data, considering the applicable data formats. This aspect is relevant for small and medium-sized companies, for whom carrying an LCA study and/or developing DPPs can represent an excessive expenditure of resources.

[1] more information on LCA and s-LCA provided in position paper of Task Force Sustainability: https://batterieseurope.eu/workstream-bodies/cross-cutting-task-forces/
[2] see also position paper of Task Force Sustainability: https://batterieseurope.eu/workstream-bodies/cross-cutting-task-forces/

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3. ADVANCED MODELLING FOR ACCELERATED BATTERY DEVELOPMENT

The battery sector is growing very rapidly and to remain competitive, companies need to accelerate their development efforts and reduce the time-to-market. Digital technologies can be a key enabler for the industry, also thanks to the ever-growing availability of computational resources and the continuous advances in modelling, coming from the scientific community. Advanced modelling and digital technologies can provide valuable support in different phases of the battery development process, but also during the deployment phase, targeting the optimisation of the entire battery value chain. Starting from the material level, automated discovery and design of battery materials can be a key enabler for the development of innovative energy storage technologies and for the continuous improvement of the currently consolidated chemistries. Advanced multiphysics-multiscale models are also crucial to support the development and design of battery cells and systems for emerging battery technologies. Battery development currently still requires complex, time-consuming and expensive testing. Digital tools can be used to minimise the need of physical testing, integrating virtual testing in the standard development process to evaluate battery performance, lifespan, reliability, and safety. Advanced modelling can also be used to design and optimise new recycling processes and additionally to evaluate how these processes can deal with the upcoming battery chemistries. Finally, digital tools can support the optimisation of the entire battery value chain and logistics, linking all steps, from raw material extraction to end-of-life (EOL), to ensure the lowest environmental impact and reduce total costs.

Adopting an open-source software approach to the development of these digital solutions will ensure scalability, flexibility and, above all, adaptability to different battery technologies, greatly benefitting the European Battery Industry.

3.1 Automated discovery and design of battery materials

The integration of automated discovery in battery development via high-throughput experimentation and advanced modelling has emerged as a key enabler in developing novel energy storage technologies. These methods allow for a more expedited development process, while at the same time contributing to the reduction of R&D costs and in obtaining superior battery performance[14,15]. This section aims to explore how these methodologies have been developed within the framework of the current EU initiatives and sets the expectations for the upcoming years, aligning with the vision and strategic objectives outlined in the Battery 2030+ roadmap[16].

High-throughput experimentation (HTE) allows for the simultaneous screening, synthesis and characterisation of large arrays of different material classes, which can lead to the identification of lead candidates for given systems and targeted applications[17,18].*Computational modelling*, encompassing electronic structure calculations, atomistic and molecular simulations, continuum modelling, and data-driven and predictive modelling, enables a comprehensive exploration of electrochemical, mechanical, thermal and structural properties of battery materials[19,20,21]. Over the recent years this approach has accelerated the ability to explore and optimise battery design,

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expediting the research process and opening new pathways for innovation in battery technologies[12]. Furthermore, machine learning and artificial intelligence are emerging as enablers to create faster and more accurate models with improved prediction accuracy, better generalisation to new conditions and the ability to incorporate complex battery behaviours.

The BIG-MAP project[22], under the Battery 2030+ initiative roadmap[23], currently represents the largest effort in developing an automated ecosystem for chemistry and technology-neutral battery material discovery. Within BIG-MAP, the materials acceleration platform (MAP) focuses on the autonomous acquisition, handling and analysis of comprehensive data sets, encompassing the full spectrum of the battery development cycle. In conjunction with MAP, the battery interface genome (BIG) initiative focuses on understanding critical battery processes happening at the interfaces, such as charge transfer reactions, dendrite formation, solid electrolyte interphase formation, and cathode–electrolyte interface development. Building upon the foundational work of MAP, BIG seeks to establish a comprehensive understanding of these interface-related processes, which are vital for the functioning of all batteries.

Additional EU initiatives with a narrower focus include the SONAR and OPERA[24] projects. The former aims to establish a framework for evaluating electroactive materials suitable for aqueous and non-aqueous redox flow batteries. This will involve a multiscale modelling approach that enhances and connects simulation methods across different scales through a blend of physics and data-driven modelling. The OPERA project aims to revolutionise solid-state batteries by developing new operando techniques and multiscale modelling strategies. These efforts are focused on understanding and optimising the interfaces within these batteries, with the aim of achieving zero-excess energy storage.

Beyond the EU initiatives, there is a significant global effort directed towards the development of computational techniques to understand and develop new battery technologies.

The advancement of HTE in battery research is increasingly characterised by an interplay between automated processes and computational models. Central to this is the accelerated experimental design of anodes, cathodes and solid electrolytes for Lithium and beyond Lithium batteries. This approach is crucial for assessing extensive candidate lists derived from combinatorial studies and for enhancing the robustness of machine learning models[25]. Complementary to this trajectory is the advent of MAPs, which combine AI, robotics and computing. These platforms expedite the experimentation process, although they are still navigating the complexities of achieving full autonomy[26].

The effective utilisation of the data generated from these technologies is a critical aspect, necessitating the integration of AI/ML algorithms. This integration is essential for enhancing decision-making processes in the development of battery materials, streamlining the journey from theoretical models to practical applications[15]. The role of AI/ML in this domain is recognised for its transformative potential. It is not just about accelerating research but also about making these tools accessible and applicable across various research contexts[27].

The global response to environmental and material challenges underscores the urgency of accelerated discovery in battery research. MAPs are at the forefront of this endeavour, advocating for a collaborative approach across industries and borders. Such collaboration is vital to achieve sustainable solutions, aligning technological advancements with the global imperative for environmental sustainability and resource efficiency[28].

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Research and Innovation Programme under Grant Agreement N. 101069676

3.2 Cell and battery design for emerging battery technologies

The battery sector is evolving very rapidly due to the large demand for batteries for both mobility and stationary applications. In this context, upcoming and emerging battery technologies will play an important role, enabling to diversify the supply of the needed materials and achieving the targeted costs and performances needed for each application sector. The availability of validated models and software tools is crucial to accelerate the technology development and reduce the time-to-market for these new battery technologies.

Models and software for lithium-ion battery (LIB) design and optimisation from cell to battery pack are currently commonly used and readily available with both commercial and open-source options, e.g., COMSOL[29], Ansys Fluent[30], PyBaMM[31], BattMo[32], cideMOD[33]. However, validated models and tools for upcoming and emerging battery technologies such as redox flow batteries (excluding vanadium redox flow battery), solid-state batteries, metal-air and metal-sulphur are still missing. For each battery technology, the required activities concern:

- The development of multiphysics mathematical models of increasing complexity to reproduce the physical phenomena affecting the cell performances;
- The implementation of the models in state-of-the-art computational tools;
- Model validation based on accurate and complete experimental datasets.

Each of these activities is crucial to ensure that the European battery industry has the needed tools to build better and lower cost storage technologies.

Battery models need to take into account several physical phenomena (chemical, electrical, thermal, mechanical) and their interactions which happen at different scales, from electrode to the system level. Each scale requires different modelling approaches that can be integrated into a multiscale modelling tool optimising this way the overall battery design. The core component of such a tool would be a continuum-scale multiphysics model for battery cell that can also be used to develop battery packs/stacks (either directly or indirectly through model order reduction).

The integration of such models in open source tools would greatly benefit the whole battery industry and community, also removing the cost barriers that can limit small companies in getting access to validated tools from commercial providers. The use of state-of-art open source computational software, such as those developed in Python, OpenFOAM, FEniCS and MATLAB, will ensure scalability, flexibility and most of all the adaptability to different battery technologies. The long-term target would be an integrated multiscale tool that could address the different industry needs. Streamlining the development efforts of the European scientific community into a single direction of an open multi-technology battery toolkit serving our European battery industry could bring important benefits in the long run.

3.3 Virtual battery testing

The current approach to battery development primarily relies on trial-and-error methods, which are time-consuming and expensive, and do not always yield optimal product designs. Existing methods and tools often incur high costs due to long test periods, the need for a large number of test samples, and the utilisation of expensive testing infrastructure. However, there is a significant potential for enhancement by leveraging digital methods and tools to minimise reliance on traditional trial-and-error processes to evaluate battery performance, lifespan, reliability, and safety. The digitalisation of battery testing will result in faster battery development, shorter time-to-market, enhanced evaluation of performance, lifespan, reliability, and safety and more accurate estimation of battery lifespan through improved modelling of battery aging and the use of digital twins. These advancements in battery testing will lead to substantial cost savings, particularly during the development phase. Recently, several initiatives have been funded by the EU to fill the existing gap, e.g., AccCellBaT[34], THOR[35], FASTEST[36] and DigiBatt[37]. However, several challenges still need to be addressed.

One of the main challenges concerns the development of virtual methods to reduce the complexity, costs and time related to testing from cell to system level. Integration of models (both physics-based and data-driven) with real data coming from physical testing at smaller scale or sub-component level will reinforce the prediction capabilities of these methods. Research is also needed on the standardisation of battery system testing & validation approaches focusing on the fusion of physical and virtual test methodologies. These approaches, combined with the development of simplified testing strategies, will make it possible to reduce the number of physical tests required and their complexity, while improving the safety and reliability of batteries. Finally, it is crucial to understand the impact of different operating loads, failure modes, ageing and misuse on battery reliability and safety of batteries and to highlight the dependencies between them in order to design the most adequate testing methods and parameters.

3.4 Modelling tools for improved EOL, including sorting and recycling

The transition towards a circular economy requires sustainable waste management to reduce its adverse impacts on the environment and human society. Such a management should close the product value chain to reduce the use of resources and raw materials, ensuring current and future access to these resources. This is strategically important for a secure and sustainable supply of critical raw materials to increase resilience and security of a society. In the context of batteries, the EU has already implemented appropriate measures (e.g., EU battery Regulation), to ensure the development of a sustainable circular value chain for batteries in Europe. In this regard, recycling plays a key role in closing the value chain of different battery technologies. In fact, the EU Battery Regulation establishes strict measures on the recycling efficiency of end-of-life batteries and the amount of recycled material to be used in manufacturing of new batteries. Therefore, great attention should be paid to developing recycling processes that comply with battery regulations, especially in view of the lack of established sustainable and economic recycling routes for current and next generation lithium-ion batteries, batteries based on new chemistries and other battery technologies such as redox flow batteries. In this regard, the use of models to bridge the gap in battery recycling is crucial to keep up with the increasing pace of technological change fostered by the influence of digitalisation in various fields.

An interesting topic is the development of reliable physics-based models for chemical processes that have potential use in the recycling of batteries. These models can be used to assess the viability of the processes developed for new battery chemistries and technologies. In addition, they can facilitate the scale-up, optimization and control of chemical processes to achieve higher recycling efficiency, lower energy consumption and reduced CO_2 emissions. For instance, the hydrometallurgical recycling route

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for end-of-life Li-ion batteries relies on chemical steps such as leaching, liquid-liquid extraction and precipitation. And reliable models can facilitate the development or adaptation of these steps as new chemistries are introduced into the market. Focusing on the diversity of chemistries, promising modelling frameworks can be beneficial to evaluate the flexibility of a particular process to handle changes in the composition of feeds received by recycling plants. In addition to physics-based models, data-driven or hybrid approaches are needed to estimate the performance of those recycling steps for which a physical description is not yet available.

Another topic of interest is the direct recycling of battery active materials, particularly for Li-ion batteries. Models, either physics-based or data-driven, can serve to predict the nature of degradation of active materials by examining the battery's life history, possibly available through the battery passport, which is essential for successful direct reconditioning of active materials.

Lastly, it is important to note that modelling tools for steps of recycling processes can be integrated into digital twins of recycling plants for the purpose of process control and optimized operation.

3.5 Battery value chain optimisation

In advancing our research approach within the battery research and industry, one of the main priorities is to bridge the gap between digital tools and the entire value chain, from raw material extraction to manufacturing, product utilization and eventual recycling. Traditionally, research has been compartmentalized into specific elements within the battery value chain, often overlooking the need for a holistic perspective. To achieve a comprehensive understanding, it is imperative to establish connections between these elements and integrate them into a larger framework. This integration necessitates interoperable data structures that facilitate connectivity between neighbouring domains and contribute to optimizing the entire value chain for sustainability (s. section 2).

Leveraging forward and reverse computer aided engineering techniques is crucial in this endeavour, allowing us to refine designs and processes iteratively. The application of *digital product life cycle management* serves as an aggregating concept, ensuring a seamless flow of information and insights throughout the entire life cycle.

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4. DIGITAL TWINS

4.1 Introduction

The concept of the *digital twin* has gained significant attention since it was first mentioned in a NASA publication in 2010[38,39]. Digital twin is understood in this chapter as a virtual representation or digital counterpart of a physical object, process, system or entity that incorporates real-time data and simulation capabilities, enabling it to accurately reflect the behaviour and changes of its physical counterpart over time.

There are numerous examples that illustrate the versatility and wide-ranging applications of digital twins in various industries, demonstrating how they contribute to improving efficiency, decision making and overall performance. In this context, core elements describing a digital twin are the physical world, the virtual world, and the flow of data between the physical asset and its virtual representation[40]. The quest of developing battery digital twins involves several technical advancements across various domains. Here are all key areas that should be considered in order to succeed in building robust and reliable DTs in the battery sector:

- **High-fidelity battery models**: Develop advanced battery models that accurately represent the real assets, incorporating detailed physics to simulate battery manufacturing and performance under different operating conditions.

- **Real-time monitoring and diagnostics**: Implement robust real-time monitoring systems to collect data on key battery parameters. Additionally, this implies the integration of sophisticated diagnostic algorithms capable of detecting early signs of degradation, faults, or abnormal behaviour.

- **Sensors and instrumentation**: Explore and implement novel sensor technologies to enhance the granularity of data collection, capable of monitoring internal conditions within the whole battery value chain.

- **Data integration**: Establish frameworks for seamless integration of data from various sources, including sensors, historical performance data, and external environmental factors. This should also include the implementation of data fusion techniques to create a comprehensive and accurate representation of real assets.

- **Machine learning algorithms**: Utilise machine learning algorithms to analyse vast amounts of data and identify patterns. Then train models to predict future battery performance based on historical data and real-time input.

- **Cyber-physical systems integration**: Integrate the digital twin with the physical assets through cyber-physical systems, enabling bidirectional communication and control. This might imply the establishment of secure communication protocols to ensure the reliability and integrity of data exchanged between the physical battery and its digital twin.

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- **Adaptive control strategies**: Develop adaptive control strategies that leverage insights from the battery digital twin to optimise charging and discharging protocols in real-time. This would involve the implementation of algorithms that dynamically adjust operating parameters to maximise performance while minimising degradation.

- **User interface and visualisation tools**: Design user-friendly interfaces and visualisation tools to enable users to interpret and interact with the digital twin. Such interfaces should then be able to provide actionable insights and recommendations for maintenance or operational adjustments based on the digital twin's analysis.

- **Continuous learning and improvement**: Establish mechanisms for continuous learning and improvement, allowing the battery digital twin to adapt and evolve over time as new data and insights become available.

- **Integration of the digital twin in the company management system**: The integration of the digital twin with other tools, as for example enterprise resource planning software or product life cycle management tools. This will allow a more effective practical utilisation of digital twin in practice, and even to incorporate economic and/or environmental parameters in it. Furthermore, this approach will enable leveraging the digital twin for supporting process improvement and optimisation, while also facilitating the comprehensive integration of batteries lifecycle into those processes

Here are additional considerations related to security, standards, and communication that are important to pay attention to while developing digital twins:

- **Digital twin validation**: A key aspect when developing, implementing, and using in practice a digital twin is the question of how well it represents reality. Hence, special attention should be given to its validation, that should be based as much as possible on real life of the process operations, or from the stakeholders of the battery value chain. Questions of data quality and/or uncertainty should be addressed here when performing the validation.

- **Digital twin updating**: As technology, regulations, strategies, and other relevant aspects directly related to the battery sector keep evolving, updates of the implemented digital twin are required from time to time. This can be an activity with a defined periodicity or done when it is required. In this updating process, data and/or information from the various stakeholders involved in the battery value chain should be used to ensure that the new iteration of the digital twin improves when compared do the previous one.

- **Communication protocols** that facilitate communication between the physical object, sensors, and the digital twin. Common protocols include MQTT (Message Queuing Telemetry Transport), CoAP (Constrained Application Protocol), and HTTP (Hypertext Transfer Protocol).

- **Cybersecurity protocols** and measures to protect the digital twin and the data it handles from unauthorised access, breaches, and cyber threats. The new protocols may be based on already existing data exchange and traceability, as for example blockchain, or specifically designed for battery systems.

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- Adherence to **industry standards and protocols** to ensure interoperability, compatibility, and consistent data exchange between different digital twin implementations.

The integration of these elements and considerations will ensure the creation of a robust, accurate, reliable and effective Digital Twin system, capable of providing valuable insights, optimising processes, and facilitating better decision-making. Additionally, addressing communication, security, and industry standards will enhance the reliability and trustworthiness of the digital twin environment.

4.2 Implementation of digital twins in the battery value chain

The digital twin concept is recognised as a pivotal element in the digitalisation era of the entire battery value chain. Thus, from the initial conception phase through the manufacturing process, where raw materials are transformed into cells meeting specified requirements, to the critical testing phase encompassing crucial steps such as formation and aging studies, the digital twin emerges as a vital method for accelerating the development phase.

4.2.1 Battery cell manufacturing

The scope of digital twins in battery cell production is very broad and can range from a digital twin of a building to a digital twin of a machine or asset, to a digital twin of a product (i.e. battery cell)[41]. *Digital twins for buildings* usually describe the building information model (BIM) and aggregate contents of environmental effects and dependencies such as energy consumption, logistic simulations and building automation for monitoring and control. This will enable building managers to make data-driven decisions and adjustments before the actual operation. On the other hand, *digital twins for machines* provide a dynamic and responsive representation of a manufacturing equipment, offering benefits such as adaptive processes, predictive maintenance, and overall operational optimisation. Furthermore, a *digital twin of a product s*erves as a virtual representation that captures and integrates information throughout the entire production process[42].

The successful integration of digitalisation approaches in an automated production line holds the promise of significantly reducing the overall costs of battery cell production. By leveraging digital technologies such as internet of things (IoT) and AI/ML, manufacturers can streamline processes, optimise resource utilisation, and minimise waste, leading to increased efficiency and cost savings. Automation allows for precise control and monitoring of production parameters, resulting in higher quality output and fewer defects. Additionally, digitalisation enables real-time data analysis and predictive maintenance, helping to prevent costly downtime and equipment failures. Overall, the integration of digitalisation in battery cell production represents a key strategy for improving competitiveness and sustainability in the industry.

4.2.2 Battery cell testing

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The concept of a digital twins in cell testing follows a similar philosophy to other digital twin applications, such as digital twin manufacturing and state-of-health (SoH) estimation control. The primary focus is on leveraging virtual representations to accelerate and enhance the understanding of the performance of cells being tested in the laboratory. In this context, digital twins in cell testing will aim to accelerate the testing processes by providing a virtual environment where simulations and analyses will be performed, reducing the time required for physical testing and allowing for a more rapid iteration of experiments. Additionally, integrating real-time data from physical tests into the digital twin will enhance its accuracy and reliability and will give the opportunity to researchers to compare virtual predictions with actual test results. As a result, this will enable the improvement of the digital twin model over time.

In essence, the digital twin concept in cell testing is a powerful tool for researchers seeking to advance their understanding of battery cell behaviour. It aligns with the broader trend of leveraging digital twins across various industries to enhance efficiency, optimise processes, and drive innovation.

4.2.3 Battery operation

The effective and efficient management of lithium-ion batteries is crucial for low-carbon applications, such as electric vehicles and grid-scale energy storage. The lifetime of these batteries is intricately tied to various factors, including materials, system design, and operating conditions. The complexity of factors affecting battery performance has made real-world control of battery systems challenging and recent advancements in understanding battery degradation, modelling tools, and diagnostics present an opportunity to overcome these challenges. In this context, there is a prospect to integrate knowledge about battery degradation, modelling tools, and diagnostics with emerging machine learning techniques. This integration aspires to the birth of the concept known as the *battery digital twin*, which involves a close interaction between the physical battery and its digital representation. The envisioned outcome is a battery digital twin that facilitates smarter control, ultimately allowing for a more intelligent and interconnected approach contributing to a potentially extended battery lifespan[43,44,45,46].

The successful integration of these technical developments will pave the way for a sophisticated battery digital twin, revolutionising the management and optimisation of batteries in diverse applications. Additionally, the deployment of sophisticated battery digital twin frameworks might enable strategies for the second use of batteries. In particular, leveraging accurate battery models, continuous monitoring systems, and advanced sensors, such frameworks could assess the remaining useful life of batteries post their primary application. For example, by integrating data from historical performance and employing machine learning algorithms, these models could predict the performance of batteries in potential second-life scenarios. Moreover, the cyber-physical integration ensures real-time insights, enabling decision-makers to evaluate a battery's health and suitability for repurposing. This, of course, should imply security measures, including robust protocols for data handling, addressing privacy concerns associated with the battery's first-life information. Overall, by identifying batteries suitable for a second life, the digital twin concept helps in reducing the generation of electronic waste.

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4.3 SoX monitoring

In the rapidly evolving landscape of energy storage, the efficient management of Lithium-Ion batteries (LIB), in particular for electric vehicles (EV), has emerged as a critical concern. It is paramount to maximise battery pack performance in real time operation, ensuring safety, optimising energy efficiency, while at the same time obtaining accurate assessment of the battery's health and operating conditions. In this regard there is a significant need for implementing State-of-Health (SoH), State-of-Charge (SoC), State-of-Energy (SoE), State-of-Power (SoP), and the innovative concept of State-of-Safety (SoS) monitoring tools. These terms are collectively referred to as state of X (SoX), in battery management systems (BMS) for the batteries of the future (see *Figure 1*).

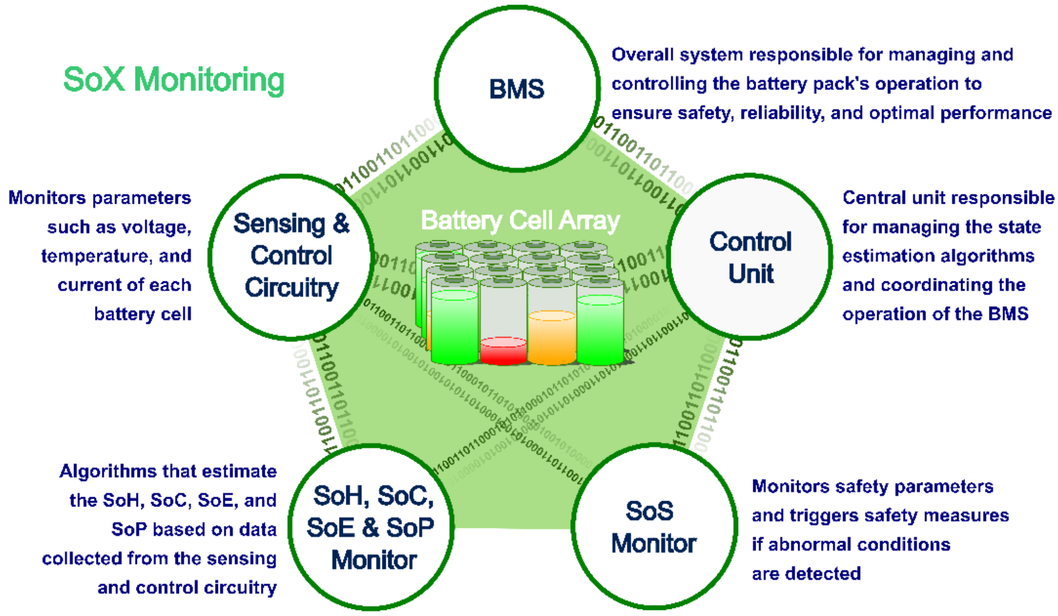

Figure 1: Integrating digital technology to create SoX monitoring systems for enhanced battery performance and safety.

4.4 SoH/SoC/SoE/SoP monitoring

SoH, the remaining capacity relative to the original capacity, stands as a key indicator in understanding the degradation performance of LIBs. Accurate SoH estimation is essential for prolonging battery lifespan and preventing unexpected failures. Traditional approaches, such as *Coulomb counting* [3] and model-based estimation, have paved the way for reliable SoH assessments but often require a full charge/discharge cycle, a process that can be time-consuming and lengthens the diagnostics phase. This is because these methods rely on capturing comprehensive data throughout the entire charging and discharging process to accurately assess the battery's health status. The recent introduction of digital twin frameworks offers a paradigm shift by enabling real-time SoH estimation without the need for complete discharge cycles. This capability not only enhances the accuracy of SoH assessment but

[3] calculating the remaining capacity by accumulating the charge transferred in or out of the battery

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also allows for proactive measures to be taken during ongoing cycles, minimising the risk of unexpected degradation.

Both SoC, representing the current level of charge stored in the battery, and SoE, describing the residual energy of the battery cell under specific operating conditions, play a crucial role in determining the energy availability of a battery. SoP is analogous to SoC but pertains to power rather than charge[4], considering factors such as the current charge level, internal resistance, and the ability of the BMS to regulate power output.

Effective SoC and SoE monitoring ensures optimal utilisation of the battery's capacity and energy, respectively and are integral for the reliable operation of devices. SoP is important in applications where the instantaneous power demand fluctuates rapidly, such as EVs or grid stabilisation systems. Maintaining an adequate SoP ensures that the system can respond quickly to changes in power demand without experiencing voltage drops or power delivery limitations. In this context, industrial internet of things IIoT-based digital twin frameworks, employing advanced data-driven approaches to estimate SoC/SoE/SoP in real-time, can be expected to become key enablers for technological advancement. This approach not only overcomes the challenges associated with complex battery dynamics and varying operating conditions, but could also contribute, for example, to accurate determination of EV range. The integration of this technology can revolutionise the efficiency of EVs and other applications reliant on LIBs.

From a BMS perspective, accurately assessing SoH/SoC/SoE/SoP of LIB cells typically implies combining the monitoring of voltage and current signals. Practical implementations in BMS essentially fall into three primary categories[47,48]:

- **Coulomb counting methods**: These methods involve a simplified analytical representation of the battery, using current integration to compute SoC and SOP. SoH is updated by referencing manufacturer datasheets.

- **Model-based estimation methods**: In this approach, battery cell models are employed to deduce SoC/SoH. One widely-used model type is the one based on electrochemical models due to their strong abilities to capture both kinetic and charge transfers inside a battery, further resulting in a highly accurate SoC indication. Another model type is the equivalent circuit model that utilises the electrical circuit components to emulate battery dynamics. Online estimators or adaptive filters correct measurement errors and deviations from the estimation. This method enhances accuracy by leveraging predictive models.

- **Data-driven methods**: Using an input-output approach (black-box models), this method employs estimators based on fuzzy controllers, neural networks, and support vector machines. These data-driven techniques do not rely on detailed knowledge of the battery's internal mechanisms and can adapt to various scenarios.

These methodologies offer diverse approaches to assess battery cell states, each with its strengths and applications. Coulomb counting provides simplicity and reliance on manufacturer data, model-based estimation enhances accuracy through predictive models, and data-driven methods offer flexibility by

[4] i.e. typically refers to the available power output capability of a battery at a given moment

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utilising black-box models for estimation. The choice of the most suitable method depends on specific application requirements and the level of detail and adaptability needed in the assessment process.

4.5 SoS monitoring

Introducing the concept of SoS can further elevate the monitoring capabilities of BMS. SoS encapsulates the overall safety status of the battery, considering factors such as thermal stability, internal resistance, and the potential for catastrophic events. However, tackling real-time monitoring of SoS requires a holistic approach to battery data management. What sets SoS apart from other states is its impartial nature. Unlike SoH/SoC/SoE/SoP, which consider tailored estimators for distinct applications, SoS focuses solely on the possibility of a dangerous reaction at any given moment, quantifying the risk even when the storage system is inactive. This distinguishing feature renders SoS applicable to various energy storage systems beyond batteries, encompassing fuel cells and supercapacitors, given the identification of appropriate safety limits.

Integrating SoS into BMS aligns seamlessly with existing charging and energy management systems prevalent in EV and charging stations. The ability to calculate SoS online, akin to the online estimation of SoC, empowers the BMS to make real-time decisions aimed at reducing the likelihood of abuse and potential hazards. A notable example involves a car manufacturer responding to a fire incident post-charging by introducing a software update to mitigate unsafe charging conditions, underscoring the adaptability and proactive nature of SoS implementation. In hypothetical scenarios, SoS could prove invaluable in post-event calculations, such as after a mild EV crash. Leveraging information from sensors pre- or post-crash, the BMS could calculate SoS, providing critical warnings to passengers and first responders about imminent hazards. This potential application showcases the real-world impact of SoS in enhancing safety protocols and response mechanisms.

From a practical viewpoint, a promising avenue for estimating SoS in BMS is the digitalisation of impedance measurements. Several methods can be envisioned:

- **Real-time monitoring with online impedance analysis**: Implement real-time monitoring of impedance over a range of frequencies using digitalised measurements during the battery's operation. This continuous analysis can allow for the immediate detection of deviations from normal impedance levels, offering insights into aging mechanisms and signalling potential safety risks.

- **Machine learning algorithms for pattern recognition**: Integrate ML algorithms that can analyse patterns within the digitalised impedance measurements. Train the ML model to recognise abnormal impedance behaviour associated with hazardous conditions, enabling the BMS to predict and mitigate potential safety issues.

- **Correlation with environmental factors**: Correlate digitalised impedance measurements with environmental factors such as temperature and humidity. Changes in these variables can impact battery safety, and by integrating them into the analysis, the BMS can enhance its ability to estimate SoS accurately.

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- **Digital twin framework for predictive analysis**: Develop a digital twin framework that replicates the battery's behaviour using digitalised impedance measurements and communicates with the physical battery. This virtual representation can undergo predictive analysis to simulate various operating conditions, helping the BMS anticipate safety concerns before they manifest in the physical battery (s. section **Error! Reference source not found.**).

- **Integration of multi-sensor data**: Combine digitalised impedance measurements with data from other sensors within the battery system. Integrating information on voltage, current and temperature alongside impedance can provide a holistic view, enhancing the BMS's ability to estimate SoS accurately.

- **Advanced signal processing techniques**: Apply advanced signal processing techniques to digitalised impedance data. Techniques such as wavelet analysis or Fourier transforms can extract valuable information from impedance measurements like distribution of relaxation times (DRT), aiding in the identification of potential safety risks and help estimating different aging routes that might be used to change battery management strategies to increase remaining useful life (RUL)

- **Continuous calibration and validation**: Implement a continuous calibration and validation process for the algorithms used in digitalised impedance analysis. This ensures that the SoS estimation remains accurate over time, accounting for variations in battery behaviour and characteristics.

By integrating these methods, a BMS can harness the power of digitalised impedance measurements to estimate SoS effectively, offering a proactive and data-driven approach to battery safety management. Moreover, the accuracy and reliability of SoS assessment methods can be further bolstered by refining its subfunctions and adjusting existing parameters. While safety limits can be initially chosen through empirical methods, the wealth of global battery safety tests provides an opportunity to incorporate more statistical data. Additionally, delving into the probabilities of failure for individual components, such as electrodes, separators, and electrolytes, presents avenues for enhancing the predictive capabilities of SoS. Crucially, the interlinked nature of SoS subfunctions, akin to a chain, emphasises that the overall safety is determined by the weakest or most unsafe link. This inherent connectivity underscores the need for comprehensive research to fortify each subfunction, ensuring that safety metrics decrease rapidly as necessary.

Overall, SoS heralds a new era in battery safety management, offering a quantifiable measure of potential hazards independent of usage scenarios. Its digitalisation and integration into BMS promise a proactive approach to safety, adaptable decision-making, and enhanced response capabilities. The ongoing refinement of SoS through research on subfunctions and component probabilities underscores its potential to redefine safety standards across diverse energy storage systems. As the energy landscape continues to evolve, SoS stands as a beacon, illuminating the path toward safer, more resilient energy storage technologies.

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5. CONCLUSION AND RECOMMENDATIONS

In conclusion, the following recommendations summarise the most important topics addressed within this position paper and can be used as a guideline for enabling advancement in the related technology domains

5.1 Common infrastructure, data shapes and ontologies

- **Common data structures, ontologies, data shapes, and interfaces** are crucial for Catena-X and other data space initiatives, enabling shared digital services.
- **Implementing a digital passport system for batteries** should be based on Catena-X and domain ontology like BattINFO and BVCO.
- **Linking machine-readable knowledge with experimental data** in battery data spaces allows for hybrid models that combine statistical, physical, and expert knowledge.
- **Consistent ontologies** in both sustainability and materials, engineering and production research will enable sustainability by design with early feedback loops

Common data structures, aligned ontologies, derived data shapes, and generated interfaces are crucial for data space initiatives such as Catena-X[49]. These structures and frameworks facilitate the population of data spaces with content from a diverse community, enabling data scientists, AI/ML experts, and simulation experts to offer shared digital services based on interoperable data. By linking machine-readable knowledge with experimental data in battery data spaces, hybrid models can be created that incorporate statistical and physical models alongside expert knowledge. The use of a consistent ontology in life cycle assessment (LCA) documents for both chemical aspects at the cell level and the engineering/production process domain is recommended. Additionally, it is suggested to implement a digital passport system for battery materials and parts within the supply chain, especially for recycling materials. This should involve the development of a common ontology for battery passport and digital twins, building upon existing ontologies like BattINFO[50] and BVCO[51].

5.2 Advanced modelling for accelerated battery development

Advanced modelling and digital technologies are becoming a key asset for accelerating the battery development process. The advancement of battery materials through automated discovery hinges on a holistic approach, integrating computational predictions with experimental data to deepen our understanding of battery behaviour and validate models effectively. This entails aligning goals across academic and industrial sectors to ensure cohesive progress. Open science and collaboration are key drivers, advocating for transparency and efficient academia-industry partnerships. A balanced research approach, embracing both technology-neutral foundational research and specialised investigations, fosters knowledge exchange and synergy between diverse research teams. Establishing a centralised repository of automated methodologies, workflows, and protocols, with clear and extensive

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- Establish a **centralised repository of automated methodologies, workflows, and protocols** with clear and extensive documentation.
- Develop **interoperable data infrastructures and ontologised archives**.
- Develop **validated models and software tools** for, e.g., redox flow batteries, solid-state batteries, metal-air, and metal-sulphur systems, among others.
- Prioritise **multiphysics mathematical models integrated into open source computational platforms**.
- Integrate **physics-based and data-driven models with real data**.
- **Implement standardised battery system testing and validation approaches**, focusing on the fusion of physical and virtual methodologies.
- Develop reliable **physics-based models for chemical processes** involved in recycling.
- **Integrate modelling tools into digital twins of recycling plants** for process control and optimization.
- **Bridge digital tools across all stages**, from raw material extraction to recycling, to optimise the battery value chain.

documentation, will maximise resource utilisation and accessibility. Additionally, developing interoperable data infrastructures and ontologised archives will facilitate access to high-quality FAIR data (findability, accessibility, interoperability, reusability), integrating computational platforms with experimental data for high-throughput calculations.

In addressing emerging battery technologies and virtual battery testing, developing validated models and software tools for redox flow batteries, solid-state batteries, metal-air, and metal-sulphur systems, among other, is paramount. This includes prioritising multiphysics mathematical models integrated into open source computational platforms to ensure scalability and flexibility across battery technologies. Integrating physics-based and data-driven models with real data will enhance prediction capabilities and reduce complexity, costs, and time associated with physical testing. Standardizing battery system testing and validation approaches, focusing on the fusion of physical and virtual methodologies, will improve safety and reliability. For battery end-of-life (EOL) and recycling, developing reliable physics-based models for chemical processes involved in recycling will optimise efficiency, energy consumption, and CO_2 emissions. Integrating modelling tools into digital twins of recycling plants for process control and optimisation will enhance overall efficiency and performance.

AI/ML plays a crucial role, demanding the development of models that harmonise predictive power with physical constraints, trained on comprehensive datasets covering synthesis to testing phases. Moreover, exploring novel AI/ML architectures such as transformer models can enhance molecular modelling and property predictions. Multiscale modelling bridges simulations across various scales, leveraging machine learning for parameterisation and model scaling. Advancements in automated characterisation and synthesis are essential, requiring the refinement of high-throughput methods and the establishment of efficient infrastructures for sample transfer and testing.

Finally, optimising the battery value chain necessitates bridging digital tools across all stages, from raw material extraction to recycling. This comprehensive approach ensures the integration of digital methods with traditional processes, fostering sustainability and efficiency across the entire battery value chain.

In summary, the integrated approach outlined emphasises coordinated efforts across disciplines, transparent knowledge dissemination, and the strategic utilization of AI and multiscale modelling to drive innovation in battery material discovery.

5.3 Digital twins

- A **sophisticated battery digital twin** will be indispensable across the entire battery value chain.
- These transformative digital twins will revolutionise battery management and optimisation across diverse applications, **spanning from initial conception and manufacturing to testing stages and final usage**.
- Overcoming challenges such as the lack of standards, models, interoperability issues, and efficiently integrating real-time data into a centralised data warehouse, **digital twins will serve as a cornerstone for accelerating battery development, reducing cost, and promoting environmental sustainability**.

The versatility and potential applications of digital twins across different actors have contributed to the absence of a single, comprehensive definition of the digital twin. While there are general understandings of what digital twins entail, their specific implementation and scope can vary significantly depending on the context and target. This flexibility is both a strength and a challenge, as it allows organisations to tailor digital twins to meet their specific needs but also makes it difficult to establish a standardised definition. Moreover, the evolving nature of technology and its applications is also contributing to the complexity of defining digital twins. As technologies advance and new possibilities emerge, the concept of digital twins may continue to evolve, making it challenging to pin down a static and universally applicable definition. In this sense it is important for stakeholders, researchers and practitioners to collaborate and share insights to develop a more standardised understanding of digital twins, even as the technology continues to evolve and find new applications.

In any case, the seamless incorporation of digitalisation approaches in the whole battery value chain holds the promise of significantly reducing the overall costs of battery cells. However, there are several challenges that must be addressed to move towards the digitalisation:

- First, while sensors and actuators play a crucial role in enhancing the quality of produced batteries and monitoring the production process, their current use is mainly limited to basic safety functions and defect detection. There is a need to explore and develop research activities focused on integrating intelligent sensors into existing production and testing facilities, enabling manufacturers and researchers to adopt agile methodologies and make real-time changes to processes and tests that can enhance battery cell performance.

- Second, the interaction between physical components and the virtual data layer of the real asset must be integrated efficiently. This involves considering technologies for data acquisition, storage and processing to enable the prediction of the impact of production changes on battery component structure and final cell performance.

- Furthermore, the vast and heterogeneous data generated in any point of the battery value chain poses a challenge for data storage, processing, and interoperability. Tools to support the

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interoperability of battery manufacturing data and models used in digital twins are essential for seamless integration and simulation across different processes and equipment.

- Lessons learned from other industries, such as automotive and machining sectors, should be implemented in the battery field to encourage the use of common languages, interfaces, and protocols. In this sense standardised communication protocols and intelligent sensor systems will facilitate data use and exchange.

- Certainly, a crucial aspect in leveraging digital models as diagnostic tools and decision-making support tools lies in defining clear interactions and information exchange between different types of models, including high fidelity and low fidelity models. This necessitates the selection of suitable strategies for coupling and synchronizing these models, which presents a new challenge in achieving the aim of digital models effectively highlighting real-world circumstances.

All in all, overcoming the challenges associated with digitalisation in battery value chain will lead to the creation of a truly connected and intelligent environment. In such a scenario, the digital twin will play a pivotal role by accurately replicating physical assets and processes in the digital realm. This virtual representation will enable more effective monitoring, optimisation, and prediction of the corresponding physical battery chain throughout its lifecycle.

5.4 SoX monitoring

The implementation of SoX monitoring tools represents a crucial advancement in the field of battery management. The integration of real-time SoH, SoC, SoE, SoP, and SoS digital monitoring, facilitated by innovative physics-based and data-driven approaches embedded into digital twin frameworks, offers a comprehensive solution for the challenges posed by dynamic operating conditions and varying states of charge. As LIBs continue to dominate energy storage in commercial, industrial, and EV applications, harnessing the power of SoX monitoring tools into *intelligent* BMS is essential for unlocking their full potential, ensuring safety, and ushering in a new era of efficient and sustainable energy utilisation. Overall, employing intelligent BMSs for safe operation and optimal lifespan, coupled with an appropriate battery model, enables optimisation in battery design and use, including battery operating system components such as thermal management systems, protections, and electric drivers.

- **Enhancing data acquisition and analysis**: To improve accuracy and reliability in battery assessment, consider investing in robust data acquisition systems and analysis tools. This will enable more precise Coulomb counting and model-based estimation, leading to better decision-making regarding battery management.
- **Integration of machine learning techniques**: Explore the integration of machine learning techniques into data-driven methods for battery estimation. This could involve developing or utilising advanced algorithms to extract insights from complex data sets, thus enhancing flexibility and adaptability in battery assessment.
- **Continuous monitoring and optimisation**: Implement continuous monitoring of battery performance and condition, coupled with real-time optimisation strategies. Intelligent BMS systems can play a crucial role here by dynamically adjusting operational parameters to maximise safety and lifespan while meeting performance requirements.
- **Investment in battery modelling research**: Allocate resources towards research and development in battery modelling to refine existing models and develop new ones. This will contribute to more accurate predictions and optimisations in battery design and utilisation, especially concerning thermal management and protection systems.
- **Collaboration with battery manufacturers**: Foster collaboration with battery manufacturers to access detailed data and insights into battery behaviour and characteristics. This partnership can facilitate the development of tailored estimation methods and optimisation strategies aligned with specific battery chemistries and designs.
- **Cybersecurity aspects**: Cybersecurity at the hardware level is becoming increasingly important in today's interconnected world. With the rise of cyber threats and attacks, it is essential to take conscience and ensure the safety and privacy. By adhering to the regulations and guidelines set forth by the EU and other cybersecurity agencies, battery manufacturers can help mitigate risks and build trust. Ultimately, cybersecurity at the hardware level is not just a requirement, but a crucial component of building a secure and resilient intelligent BMS.
- **Regular training and skill development**: Ensure that personnel involved in battery assessment and management receive regular training and skill development opportunities. This will empower them to effectively utilise the chosen assessment methods and adapt to evolving technologies and best practices in battery management.

5.5 General remarks on digitalisation

The process of digital transformation frequently challenges organizations to venture beyond their familiar territories, compelling them to make strategic decisions for an uncertain future. In this context, the following actions are recommended to foster digital awareness within organisations undergoing digital transformation:

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- Begin with **small-scale initiatives**.
- Participate in **standardisation** efforts.
- Assume responsibility for **data ownership and ethics**.
- Drive the change process and secure organizational commitment on the **digital transformation**.

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Research and Innovation Programme under Grant Agreement N. 101069676

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Batteries Europe

Position paper

Safety
Task Force

April 2024

In cooperation with
BEPA
Batteries European Partnership Association

ACKNOWLEDGEMENT

Batteries Europe Secretariat is an EU-funded project that has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676.

DISCLAIMER

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This project has received funding from the European Union's Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

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Acknowledgements: We would like to thank Spyridon Pantelis (EERA) for the overall coordination of the Task Forces, Alessandro Romanello (EIT InnoEnergy) as coordinator of Batteries Europe, and the BEPA Secretariat for their support in the operation of the Task Force. Special thanks to Fatima Ahmed, Adeola Adeoti, Lucia Sardone (CLERENS), and Maria Luisa Fernandez Vanoni (EERA) for editorial support. We would also like to acknowledge the inputs and considerations from the European Commission, the Batteries Europe Secretariat and Batteries Europe Advisory Board.

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This project has received funding from the European Union's Horizon Europe
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ABBREVIATIONS AND ACRONYMS

Abbreviation	Definition
AI	Artificial Intelligence
ALARP	As Low As Reasonably Practicable
BESS	Battery Energy Storage Systems
BMS	Battery Management System
C&I	Commercial and Industrial
CEI	Cathode-Electrolyte-Interphase
CEN-CENELEC	European Committee for Standardization - European Committee for Electrotechnical Standardisation
CID	Current Interrupt Device
ECE	Economic Commission for Europe
EES	Electrical Energy Storage
ESG	Environmental, Social, and Governance
EUCAR	European Council for Automotive R&D
EU-OSHA	European Agency for Safety and Health at work
EV	Electric Vehicles
FMEA	Failure Mode and Effect Analysis
HIAD	Hydrogen Incident and Accident Database
IEC	International Electrotechnical Commission
IFBF	International Flow Battery Forum
ISO	International Organization for Standardization
KPIs	Key Performance Indicators
LCA	Life Cycle Analysis
LIB	Lithium-Ion Batteries
MSDS	Material Safety Data Sheets
NDT	Non-Destructive Testing
NTESS	New-type Energy Storage System
OEM	Original Equipment Manufacturer
OSHA	Occupational Health and Safety Administration
PTC	Positive Temperature Coefficient
QRA	Quantitative Risk Assessment
RFB	Redox Flow Batteries
RRM	Risk Reduction Measures
SAE	Society of Automotive Engineers
SEI	solid-electrolyte-interphase
SIL	Safety Integration Level
SIL	Safety Integration Level
SoX SoC SoE SoH SoP SoS	state of X state of charge state of energy state of health state of power state of safety

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SSbD	Sustainable and Safe by Design
TR	Thermal Runaway
UL	Underwriters Laboratories
UNECE	United Nations Economic Commission for Europe

1 INTRODUCTION

Batteries as Electrical Energy Storage (EES) can largely fulfil the needs of our mobile society to store energy, and to reach the goal of becoming a sustainable society by relying on renewable energy sources, which need to be flexibly stored in order to be available when needed, as renewable energy availability is highly variable leading to mismatches between supply and demand. There are various electrochemical storage technologies which can be suited depending on the final purpose. As shown in *Figure 1* energy storage installations are projected to reach a cumulative 411 gigawatts (or 1,194 gigawatt-hours) by the end of 2030 worldwide. That is fifteen times the 27GW/56GWh of storage that was online at the end of 2021[1].

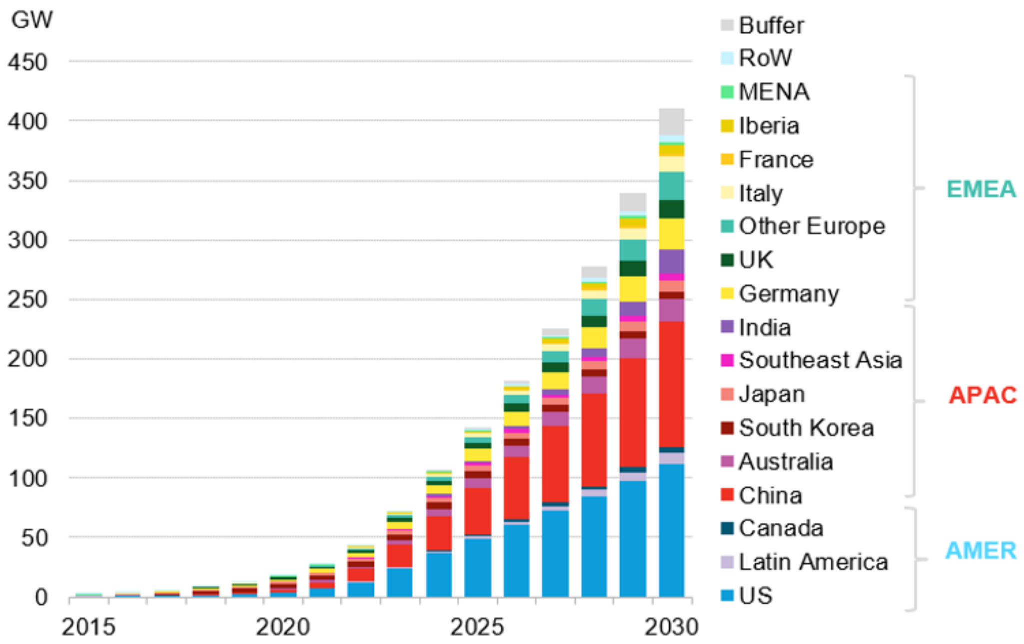

Figure 1: Global cumulative energy storage installations, 2015-2030[1]. (BloombergNEF, 2022)

Figure 2 shows the installed electrochemical storage capacity for some European countries, where it is possible to observe the large differences between them. Even though the observed differences may be due to different renewable energy development strategies between the various countries, as for example focus on hydrogen or Power-to-X for energy storage, *Figure 2* shows that there is strong potential for growth for electrochemical-based storage, in which batteries is the dominant technology.

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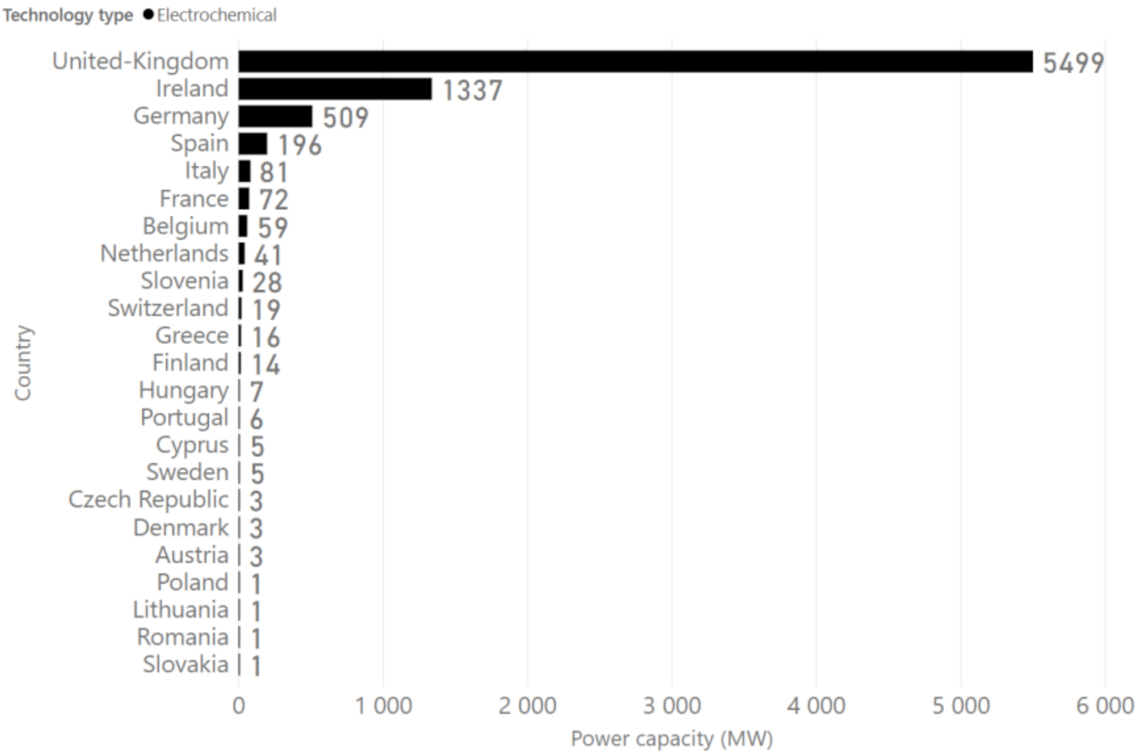
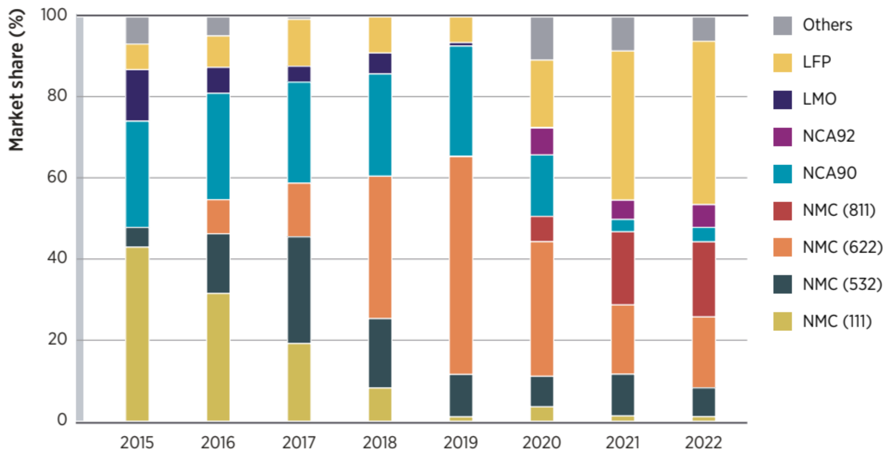


Figure 2: Electrochemical storage facilities (in operation and as project) – Power capacity by country Source[2]: (European Commission Study on energy storage, 2020)

It is essential to consider also technological innovation effects such as rapidly changing global EV battery chemistry mix, especially between 2015 to 2022, according to the IRENA study "Geopolitics in energy transition"[3] shown on *Figure 3*.



Source: (BNEF, 2022b).

Note: The numbers following NCA indicate nickel's proportion in the NCA battery chemistry, whereas the numbers following NMC indicate nickel's proportion in the NMC battery chemistry; for example, NMC (622) means 6 parts of nickel, 2 parts of manganese and 2 parts of cobalt. LFP = lithium iron phosphate; LMO = lithium manganese oxide; NCA = nickel cobalt and aluminium; NMC = nickel manganese and cobalt.

Figure 3: Rapidly changing global EV battery chemistry mix based on disruptive innovations and world-wide geopolitical situation influencing prices of critical materials between 2015 to 2022[4].

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The main goal of this Task Force position paper is to identify the coming challenges of the cross-cutting topic 'Safety' along the whole battery value chain. Each battery technology has indeed its own safety specificities and associated risks, ranging from simple battery failure to more serious events, such as thermal runway and explosion. For example, for Lead Acid batteries two significant risks are the spilling of the electrolyte, which is a danger for the human and the environment, and the production of hydrogen which is highly flammable and potentially explosive. Sodium-based batteries, in which the main risk is the presence of water reactive material (sodium metal) can lead to fires that are difficult to control and extinguish. Supercapacitors contain flammable electrolytes (acetonitrile) which may emit explosive gases in case of incident. Another example could be RFBs, where no TR occurrences have been reported; however, the electrolytes can be corrosive, as seen in the case of vanadium flow batteries, which utilise concentrated sulfuric acid solutions. The utilisation of non-corrosive, milder pH and aqueous electrolytes would help to avoid spillage associated risks, limit exposure in maintenance operations and improve the overall safety of the batteries.

Even though safety should be tackled in all battery technologies, in this report, the focus has been placed on LIBs due to their current widespread utilisation in everyday life devices. Most research efforts are concentrated on improving battery performance and durability. However, battery safety is paramount to instil confidence and facilitate widespread adoption of the energy system transition in our society. In the current document special attention is given to the following challenges: future developments of battery technologies, automatization and the use of robotics in the processes, digitalisation, while sustainability actions and education needs have been considered as well. Even though the report is mainly focused on LIBs, it could also form the foundation for safety guidelines applicable to other battery types, fostering a unified approach to safety for both existing and future developments.

A battery can introduce a wide range of hazards: electrical danger, electrolyte leakage, toxic and explosive fume emission, heat emission, flame production, fragments projection and explosion. In this regard, substantial efforts have already been made to tackle safety of batteries which is addressed in several safety standards and regulations produced by private or public bodies (ISO, IEC, CEN-CENELEC, UNECE). This work ensures already a good level of safety in current battery applications[4]. While drafting such standards and regulations, standardisation bodies and regulatory authorities should collaborate with the aim to avoid overlapping or mismatching actions. Following this effort since July 2023 the European Battery Regulation includes specific provisions about tests to evaluate safety parameters on BESS in comprehensive and uniform way (ANNEX 5)[5].

Besides the material risks described before, the increased digitalisation and reliance on digital systems in production/recycling processes and in battery utilisation presents other types of risks, namely cyber risks. For example, for grid-based energy storage, a delicate balance between supply and demand must be achieved, that may be disrupted by cyber-attacks. These can potentially intervene into the hardware and/or software controlling process, with the corresponding increase in operational risk as the system will not operate as intended. Hence, these risks should also be considered explicitly when designing and operating battery production/recycling or utilisation systems.

Safety in battery systems needs to be considered considering their full life cycle from the whole battery value chain perspective, from raw materials extraction and processing, cell and/or module packs production, utilisation, transportation, storage and all the way to final disposal/recycling phase.

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Moreover, safety should be a fundamental prerequisite included in the design of the battery and auxiliar systems themselves. This is one of the core principles behind the Sustainable and Safe by Design (SSbD) framework[6], proposed by the European Union for the development and or retrofitting of materials, chemicals, products, and processes. The link between safety and sustainability is evident, as safer systems will lead to less incidents of dangerous chemical spills or fires, thus resulting in lower environmental impacts and health risks. The framework consists of two steps: as (re-)design phase and an assessment phase that are applied iteratively as technology evolves and more data becomes available. For instance, specific safety data for chemicals or from batteries' utilisation. The (re-)design phase involves applying guidelines or heuristics to support the development and assessment of a chemical, product or process, within well-defined goals, scopes and system boundaries. Based on them, the assessment phase consists of a hazard and risk evaluation, that includes the exposure of the workers and users during the production and utilisation phases respectively. A Life Cycle Thinking perspective is used during the implementation of the SSbD framework, that could be applied either to new chemicals, products and processes, or to improve the safety and sustainability performance during production, use and/or end-of-life. More information on these concepts can be found in the position paper of the Task Force Sustainability.

With all the above considered, this position paper is analysing safety on several levels: 1. Material safety (design and manufacturing); 2. Safety at cell, pack and system level (design and manufacturing); 3. Safety at the use-phase: mobility and stationary; 4. End-of-life safety.

Starting at material level, in conventional batteries with liquid electrolytes, there are five key components in each cell: anode, cathode, separator, electrolyte and current collectors. In solid state batteries, separator and electrolyte functions can be integrated in one material. In the production and processing of each one specific risk may occur that may impact humans and the environment. At cell level, the different materials and chemicals come together, which may give cause to hazardous conditions. That is why compatibility of used metals, nanomaterials, composites, and special coatings need to be verified under extreme conditions or under failure of membranes, isolators etc. Therefore, the materials and their combination into a cell are both fundamental to ensure the functionality, properties and the safety of the battery. When a battery is taken into use it already consists of one or more cells, that may be combined to packs depending on the intended application. This level should, therefore, equally have proper safety features, e.g. adequate Battery Management System (BMS) and/or adequate casing and packaging. Finally, the end-of-life stage is also associated with various hazard substances related to handling, storage, dismantling and transport of waste batteries: from electrical hazard to fire, explosion, and chemical hazards. That is why it is crucial to consider various safety measures at all the stages of battery life cycle.

For all the levels tackled here, a general safety approach can be followed to identify and eliminate or mitigate possible hazards. This safety management approach consists of four main steps, as defined in the existing standard IEC 61508 "Functional safety of electrical/electronic/programmable electronic safety-related systems"[7]. This approach is visualised in *Figure 4*:

- **Step 1: Identification of the hazard**: starts with an analysis of the battery functions, and their interactions with the environment. This is called the "preliminary hazard analysis" or "hazard identification". At this stage, it is intended to cover all the aspects of the battery lifecycle: design and qualification, manufacturing, transport, use and end of life. It results in a list of potential hazards for a given application, and the associated Safety Integration Level (SIL).

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- **Step 2: Identification of the failure mode:** the potential failure mode needs to be anticipated. There is a need here to determine from the most critical and highest occurrence rates which hazards must be detected early, and what type of sensors/algorithms need to be developed to do so.

- **Step 3: Prevention:** this phase may be called the "hazard source control", it consists of setting up measures against the risks and/or the environment stressing conditions. It should include the required level of reliability suitable for the application and the conditions of reasonably foreseeable abuse.

- **Step 4: Mitigation/protection:** this phase is called the "hazard control", its objective is to minimise the potential hazards and its consequences. Concerning a battery system, the consequences of an event can be minimised through the reduction of the sensitivity, limit the reactions extent, and/or the break of the reaction chain. Limiting consequences of the potential hazard on the environment is also an important avenue: this must be developed in coordination with the application, in order to set efficient protection measures.

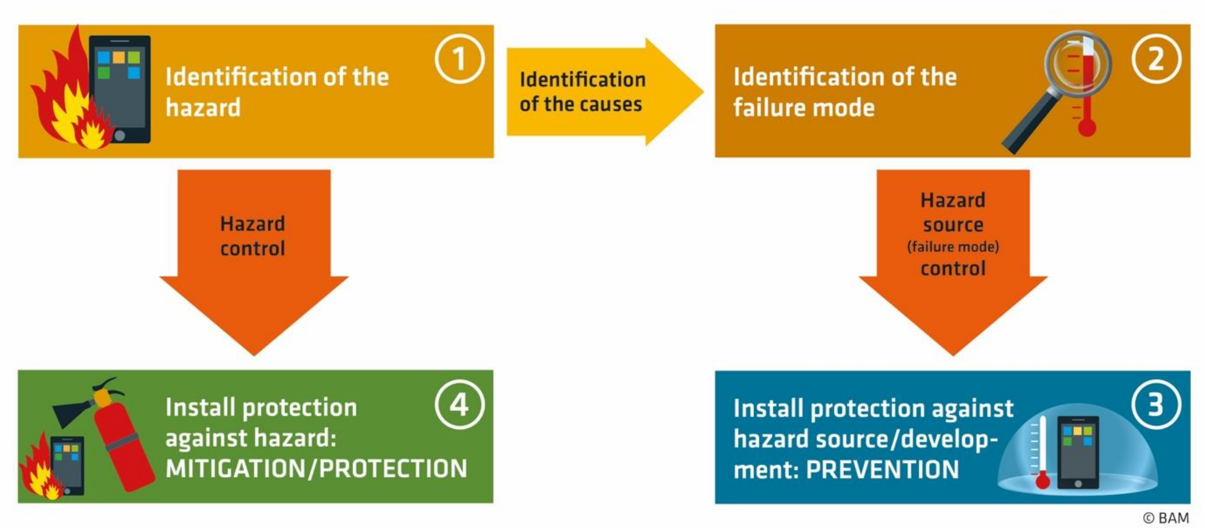

Figure 4: Schematic approach to hazard identification and remediation.

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676

2 SAFETY AT MATERIAL LEVEL - DESIGN AND PRODUCTION

2.1 Hazard Sources: discusses the risks associated with the materials used in battery manufacturing

Battery materials are chemical substances regulated under the REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) regulation of the European Union, adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals. Battery materials can have significant negative impacts on human health and environment during manufacturing, transportation, handling and processing, operation, and recycling and/or final disposal. The relevant safety properties and hazards are summarised in standardised Material Safety Data Sheets (MSDS), which provide the basic information to define appropriate processing conditions and protection measures.

Besides standard physical and chemical features of the individual materials used in lithium batteries, further hazards may result from their interactions with organics, contaminants, as well as due to their operating conditions (i.e. temperature, humidity, voltage and current). Other risks, in particular resulting from the high intrinsic electrical and thermal energy density of active materials (charged anodes and cathodes), their high electrochemical potential, unwanted processes (onset for Li-dendrite formation, temperature induced oxygen loss of cathode materials, uncontrolled interactions on Solid-Electrolyte-Interphase (SEI) and high nano-particles content, have to be considered and addressed by safety assessment on material and/or cell level.

Generally, the most severe danger comes from the triggering of exothermic reactions inside the Li-ion cell, resulting in a self-enhanced increasing temperature loop known as “thermal runaway” (TR) that can lead to bursting.

2.2 Mitigation, Prevention Actions and R&D Needs and Challenges: outlines measures and strategies to mitigate risks associated with materials and associated R&D needs

At laboratory level the risks concerning material handling are dealt with following the MSDS, that are mandatory in the REACH legislations, and standard safety procedures. Some incidents were already reported, but they can be managed with proper use of personal protective equipment and the correct collective laboratory protective equipment.

At material level, the research for safer battery materials is usually linked with the development of more stable materials. Research activities are penalised by the lack of safety assessment methodologies for the materials used in different cell components. Thus, currently no focus is given to the quantitative evaluation of novel materials regarding their potential toward increasing safety. Furthermore, the full range of safety-relevant properties for active materials, electrolyte, and separator as well as their interaction, is still not clearly defined. The large variety of materials combinations in the Li-ion battery chemistry, and also in future generation of battery chemistries

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Research and Innovation Programme under Grant Agreement N. 101069676

makes it necessary to consider safety issues in connection with single designs and concepts. For this reason, the development of a general/standardised safety assessment methodology including advanced characterisation techniques for battery materials is needed. Full safety assessment for materials should become a part of new material development for specific battery chemistry in the frame of EU-funded projects. The data gained on safety-relevant properties of materials should be implemented in a database which could be used for numerical (digital) safety evaluation, together with the physics-based models would derive safety Key Performance Indicators (KPIs) in the future but most importantly gain deeper understanding to offer further information to guide materials design.

Especially on material, electrode and separator manufacturing level, proper countermeasures should be undertaken to reduce the probability of TR. When looking specifically at storage and transportation of these materials, also the exposure to metal/carbon dusts should be mitigated at all times by applying existent regulations and developing new ones when needed. Research activities should be intensified in these fields. Possible hazards and related countermeasures should be considered in R&D, design, manufacturing and recycling, in order to provide safe and reliable LIBs for multiple applications.

Mid- and large-scale manufacturing of Li-ion battery materials must fulfil all regulatory requirements on emissions, safety, storage of chemicals etc. Especially, safety aspects in manufacturing using different synthesis routes should be considered during process development and up-scaling to provide the most safe, cost-effective and highly automated production.

Moreover, the safety during storage, transportation and handling/processing of synthesised materials is an important aspect. It is well known that some Li-ion battery materials need to be stored under special conditions (i.e. no oxygen, low moisture). Wrong storage and processing conditions can lead to the loss of functional properties (prior to application), or safety risks like exposure to metal dusts or fires.

The material design addresses morphological (particle size and shape, porosity, active surface), chemical (gradient of chemical composition, surface coating), and combinatorial (powder mixture in electrode, mixture of polymers or polymers and solids, etc.) aspects of battery materials. The multiple aspects of safety enhancement are addressed by material modifications in cathode, anode, separator and electrolyte. Material design has a great impact on the mitigation of TR, enhancement of the intrinsic safety as well as avoidance of comprehensive and expensive countermeasures on system level[8].

Improvements in material design are already applied, or in progress, to enhance the intrinsic safety of materials and to mitigate TR, taking into account materials combinations and respective interfaces in the following components:

- ***cathode,*** aim to e.g.: no exothermal decomposition during Li loss; low or no gas release due to temperature increases, or shift of O_2 release temperatures to very high values; enhanced thermal stability of cathode-electrolyte-interphase; no highly exothermal reactions with electrolyte, minimisation of corrosion and structural disordering; a more stable cathode-electrolyte-interphase (CEI) and reduce the probability for oxygen release by adding a surface coating at the cathode materials; protection against degradation of components by corrosion and the "run-off" effect of cathode material by the utilisation of binders with enhanced thermal stability (in the future, also self-healing systems) and reduced toxicity; new options for safer active materials; designing higher voltage cathodes to combine with higher voltage

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anodes to reach same cell voltage while avoiding energy stripping/plating of lithium, and consequently, enhancing the safety of the device.

- ***anode,*** aim to e.g.: high anode rate capability for high resistance against Li-dendrite formation; enhanced thermal stability of SEI and low SEI resistivity; no decomposition; no particle cracking, no build-up of contaminants, no highly exothermal reactions with electrolyte; low swelling and expansion during cycling and over the whole cell lifetime, no surface exfoliation; utilisation of anodes with a higher standard potential when compared to lithium stripping/plating; utilisation of anodes with high SiO_X and Si/C content; surface coating of anode for more stable solid-electrolyte-interphase and reduced probability of non-homogeneous lithium plating at high C-rates and low temperature; novel strategies for anode manufacturing, *in-situ* either *ex-situ*, including polymeric and ceramic coating-based approaches; minimization of material and full anode swelling and expansion during cycling
- ***electrolyte,*** aim to e.g.: additives for SEI stabilisation and protection on anode and cathode, with minimised resistance increase over cell lifetime; shear thickening behaviour by addition of oxide particles to hinder mechanical abuse; highly concentrated solutions; solid-state or semi-solid electrolytes; self-healing features; increased electrochemical stability window and onset point for SEI decomposition; fire retardant properties, shear thickening behaviour to hinder mechanical abuse; high onset for Li-dendrite formation (for solid state electrolyte only); decreasing electrolyte flammability by using non-flammable or higher flash-point solvents (for liquid electrolytes)
- ***Separator,*** aim to e.g.: fire retarding additives; improved mechanical and thermal stability at minimised thickness; multilayer structure with melting layer in the middle for disruption of ionic conductivity (so-called shut-down separators); multi-layered separators with high melting point of outer layers; good dimensional and mechanical stability adapted to manufacturing processes; fire retardant properties; cutting ion transport capability by strong temperature increase
- ***Binder,*** aim to e.g.: thermal; mechanical and electrochemical stability; high electrode stability and low swelling; improved adhesion and cohesion; low ionic and electrical resistance; low porosity reduction in electrodes.

Both existing and novel approaches target the increase of the intrinsic battery safety, by improving material design of the different components, should be recognized in upcoming EU calls and be equally considered with KPIs for performance and Life Cycle Analysis (LCA) to assess the sustainability of the whole process. As a further step, the digitalisation of KPI and databases might help improving these research and development activities.

Considering operating conditions, performance goals as well as lifetime requirements, and combining them with safety considerations (including intended and unintended misuse conditions) for a certain application, the preferential material classes can be identified and fine-tuned. For this reason, it is important that safety measures during storage and transport consider the subsequent challenges of manufacturing or recycling. Moreover, the adjustment of material properties favourable both to further manufacturing and recycling processes are of high importance. Finally, the size of battery materials or process materials stocks has to be controlled and declared according to the national and local regulations (SEVESO[9] type regulations or other).

Compared to the other parts of the value chain, manufacturing and recycling mainly differ by the high amounts of material to be processed and stored, as well as the fact that external triggers (towards TR)

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can be more severe and diversified. This means that the right risk control measures need to be put in place taking into account overall processing analysis. On material level, several countermeasures discussed in previous paragraphs can be considered to mitigate the risks mentioned above.

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3 SAFETY IN CELL/PACK/SYSTEM - DESIGN AND MANUFACTURING

3.1 Hazard Sources: focuses on the risks inherent in the design and manufacturing processes

The battery cell defines the electrochemical properties of the batteries. Accordingly, the potential hazards of the used substances and components may interact with each other creating additional hazards affected as well, by the cell design. At this stage, there are several types of hazards which may occur: chemical, electrical, thermal, a combination of them and other.

Chemical hazards are mainly associated to electrolyte spillage and gas emissions. If two incompatible components are spilled, the chemical hazard might turn into a thermal hazard. For electrical hazards, it is important to mention that the main direct hazard is linked to high voltage, but this is usually not relevant at cell level. Physical damage to the cell is also a possibility. However, the indirect hazard is the failure of electrical safety leading to a hazardous failure mode, like TR events. When a combination of chemical and electrical events occurs, it may lead to TR.

Packs are comprised of several interconnected cells, and thus the hazards associated with cells are equally applicable at pack level. The magnitude of a hazardous event, however, can be larger at a pack level, if such event affects several cells. Therefore, special attention should be given also to safety concerns at pack and also system level.

3.2 Mitigation, Prevention Actions and R&D Needs and Challenges: details strategies and actions to counteract risks in the design and manufacturing

General cell design objectives should include, next to performance and cost, the fundamental principles to ensure all aspects of safety and reliability. The design of the cell should consider the recycling phase. A well-designed cell will lead to a safer dismantling, leading to a more sustainable battery circular value chain. In order to design safe cells, there are several aspects which should be considered:

- **Identification of the potential hazards**, during expected use and reasonably foreseeable misuse. The design of the cell should therefore already include: a) The global Failure Mode and Effect Analysis (FMEA) of the batteries in its application, enabling the identification of the threats for the safe behaviour of the battery and the cells; b) The safety strategy at the battery level, enabling the allocation of the mitigation means at cell level and the various mitigation types including, mechanical, thermal and electrical protections; c) The applicable, or selected, safety standards for testing reference.
- **Design and qualification of related prevention** measures applicable at cell level, considering a) Heat exposure: assessment of cell thermal insulation and dissipation effects according to its

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internal composition and shape; b) Mechanical stress exposure: verification of the design compared to the expected level of shocks, vibrations or other threats to the cell integrity; c) Electrical protection: quality and robustness of insulation. The UN regulation for the transport of dangerous goods requires at least the robustness level corresponding to the set of tests described in the Manual of Test and Criteria, section 38.3[10], in the case of Li-ion batteries. Examples of the prevention measures could be: adding flame retardants, shut-off mechanisms inside the cell, protection circuit boards, etc.

- **Design and qualification of related mitigations** measures applicable at cell level, considering: a) Hazardous heat emissions: dissipation, thermal insulations, etc.; b) Flammable risks: materials flammability, propagation barriers, etc.; c) Internal pressure risks: size and opening pressure of the vent, breaking parts, risk of bursting, etc.; d) Hazardous gas emission: this hazard is difficult to assess but is paramount to evaluate the safety of a specific technology. Even if it is created at cell level, its mitigation is generally managed at system level; e) Hazardous substances leakages: related to the hazardous substances used and its mitigation, which is generally managed at system level.

3.2.1 Safer cell R&D

In order to minimise and prevent the potential hazards that may occur at cell level, in addition to the use of safer materials, various activities are performed. One example is the development of existing passive safety devices (CID, PTC, short circuit protection or under research actions like self-healing separators). More exploratory research focuses on a way to integrate smart sensors (optical, acoustic, electrical, thermoelectric, etc.) inside cells in order to track vital parameters[11]. Other studies start from the hypothesis that a failure cannot be avoided and try to develop cells that are not causing hazard even in case of failure: it is the “fail-safe” approach. However, much more developments are possible and should be encouraged. Additionally, development of coupled multiphysics models with Artificial Intelligence (AI) tools in predictive computer tools will be needed in order to gain more understanding and give explaining to the reasons behind non-safety scenarios. The data needed for the AI tools may come from previous experiments or from the literature, generating in a way a hybrid data driven model, where multiphysics models are combined with data, making easier to identify or to study the key parameters controlling the cell and/or battery module safety. More robust (especially for high-power operations) cell design variants, like bipolar design, could also be considered.

In case of TR, the root cause requires prevention on different outcomes such as, electrical failure, mechanical abuse, and thermal abuse. In the event of loss of functionality, the battery function level must be verified and re-established, however it may rely on a single failure at cell level. Cell level is also the best level to break the fire propagation chain. For this reason, this is an important aspect of prospective research.

3.2.2 Safety at pack level

The battery pack level holds further options for safety measures, such as: mechanical features (housing, insulation, cooling system), electrical features (BMS for management of charging, operation, temperature, system control and fault management) and operational features (protective circuit, labelling of cables, leakage protection). At the system level, there are further possibilities for increasing

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the safety of the EES application: constructional measures (fire protection doors and walls, fire smothering design), components outside the EES (sprinkler systems) and control/monitoring systems (cameras, sensors embedded in each cell etc.). All the following aspects are currently considered important for the European research activities in the different stages of EES.

To increase the safety at pack level, development and improvement of different safety features on the level are possible. To this end, the development of appropriate risk analysis tools providing the individual target specifications is useful. These tools are necessary to develop models at the laboratory scale for specific applications and respective safety levels: both down scaled models from real size level as well as computer models are essential. An important safety issue is a high temperature that can lead to a TR of the battery. Thus, innovative cooling systems (liquid immersion, phase change materials, heat pipes) with improved sensors have to be developed. Moreover, efficient warning and embedded extinguishing systems need to be implemented. In addition, construction measures involving new materials (e.g. improved insulation, fire retardant / fireproofs, etc…) and self-healing coatings should be encouraged.

3.2.3 Safety at system level

At system level the safety is primarily managed by the BMS. New and innovative safety measures will therefore focus on the BMS but are not limited to them. For this reason, it is necessary to develop and enhance intelligent BMS to monitor the SoX parameters (state of health (SoH), state of charge (SoC), state of safety (SoS))[12]. Intelligent BMS should also monitor each individual cell during storage, charging and discharging: the BMS needs to interact with sensors, shut-off and (dis)charge systems in the event of conspicuous behaviour. In case of failure, other passive systems (pressure release device, fuse, thermal insulator etc.) and active systems (embedded extinguishing systems and other) can be integrated. When designing an EES, the special requirements and conditions of a certain battery or system need to be considered. In order to improve the battery pack/system's safety design, it is necessary to develop safety performance and failure prognosis models with the aim to precisely predict mechanical/electrical/thermal behaviour of the battery (including thermal runaway and propagation)[13]. In order to minimise the risk of thermal runaway at system level, an early detection of failing cells is required. In this respect, innovative and more efficient cooling systems, coupled with monitoring devices based on new tools like thermographic devices and sensors, could be implemented.

While this report is mainly focusing on LIBs, attention should also be given to some emerging chemistries. Flow batteries, for example, cannot be tested by just characterising the flammability of the electrolytes. A more comprehensive analysis of RFB fire risks could be achieved by characterizing the fire risks of the other RFB components which have demonstrated high combustibility and would present a safety hazard in case of external fires. Components such as the gaskets, membranes, bipolar plates, electrode frames and electrodes are composed of carbon and nitrogen compounds that release toxic COx and NOx gases during combustion. The investigation of the fire risks of a fully drained cell stack would provide valuable information.

Research studies typically characterize factors affecting performance but not the safety under off-nominal conditions (e.g., overcharge, over-discharge, external short-circuit). However, the toxicity or flammability of the gases released, or the degradation and changes that occur to the flow battery components under off-nominal conditions are usually not investigated. In addition, while tests specified in *IEC 62932* are a good starting point, additional tests are needed to fully understand the mechanical behaviour and safety of flow battery stacks, testing for example vibration, liquid and gas leakage, overpressure and pressure cycling. Finally, safety tests appropriate to the credible off-nominal failure modes should be carried out at the system level to confirm safety of the entire ESS.

The increasingly digitalisation and digital integration of batteries in renewable energy systems, at small and large scales, also poses risks of cyber security, as their performance can be negatively impacted and even lead to dangerous situations, including system failures, spills or fires. Specific cyber security measures and procedures should be developed and implemented in existing and future systems, in order to precent intrusions or to mitigate their effects if they occur. Due to the fast development in the field of digital systems and security, those measures and procedures should be updated and improved regularly[14].

In addition, the outside and construction of the building or appliance where the battery is built into, needs to be designed considering structural measures and insulation as well as dimensioning of sprinklers and early warning instrumentation, involving cameras, sensors and thermographic means. The housing of EES need to be resistant to crashes, abuse or misuse. Advanced safety features include fast responding and well dimensioned venting opening and current interrupt devices when pressure increases or upon gas/smoke detection.

Specific safety testing of the design by suitable methods, including models and simulation tools need to be further developed, to ensure that the measures taken are effective. Finally, the design of the system should consider the recycling and dismantling phase. A sustainable system should allow easy dismantling of cells limiting associated risk (e.g. electrical shock, chemical hazard).

3.2.4 Safety at laboratory level

There are several hazards at cell level which may occur in the laboratory environment. Chemical hazards on one hand, should be first identified on the material level (as discussed in the previous chapter). Specific changes in materials due to electrical use (oxidation, reduction, gas emission) should be considered. It is expected that a lack of identification and classification of hazards is a common situation during the R&D stages: in this case, general laboratory protections are needed to avoid workers exposure. On the other hand, for fire hazards, flammable materials might be ignited by short circuits. In this case, general safety procedures such as suitable fire extinguishing systems and laboratories protocols should be followed.

In addition, fire hazard should not be disregarded during the storage phase in laboratories. Precautions for chemical risks, fire risk and self-ignition of cells in stock such as storage of limited quantities of stored cells, fire protection (systems and procedures), and the use of non-flammable surrounding materials, should be undertaken.

3.2.5 Safety at product manufacturing level

During manufacturing, prevention and mitigation measures should be integrated to support the products safety (according to design) and the equipment safety.

- **Equipment safety:** Cell manufacturing equipment may require the use of processes presenting risks (laser welding, high voltage, etc). In principle, safety is considered during the equipment design. Specific attention must be given to the potential mitigation measures in case of a cell-initiated event due to manufacturing faults (fire, gazes, etc..).
- **Product safety:** During cell production, a strict quality control is essential (and made mandatory by the transport regulation) to ensure safety. The risks associated with a product (cell, pack) should identified and taken into account already at the stage of design of manufacturing equipment. Both local and EU-level regulations aim to ensure safety of workers during the production work, and the compliance with these health and safety (workers protection) regulations has to be ensured (REACH, OSH and local regulations). The mitigation measures in case of an incident during manufacturing should include the scenarios of potentials hazards resulting from abused cells (chemicals release, gas release, flames etc.).
- **Handling and Storage:** Specifications related to the product hazards and robustness should be followed. When handling the product (cell, pack) it is essential to avoid shocks, heat, temperature variation, or water contact. In addition, fire precaution measures should be applied in line with the prevailing guidelines (segregations, maximum stock sizes, water sprinklers, gas extraction, air ventilation or other fire equipment, etc.). For reference, the UN regulation is specifying the package conditions according to the liability of a good to ignite a TR. For these batteries, electric abuse and metal dust emissions are important to consider. The risk should be assessed with other chemicals potentially used in the plant and other type of installation to avoid propagation of battery cell's-initiated events.
- **Worker safety and comfort:** Optimal safety and comfort conditions for people working in dry-rooms must be ensured. Normally, the dew point in these dry-rooms is between -40°C and -80°C, and these are extreme and very tyring working conditions, that might affect product quality and overall safety.

In addition, the development of safe **automatised procedures** can be used to safely produce and recycle cells and packs, limiting human interaction and decreasing the necessity for personnel in close proximity to possible dangerous situations.

This project has received funding from the European Union's Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

4 SAFETY IN THE USE-PHASE IN MOBILITY AND STATIONARY APPLICATIONS

4.1 Hazard Sources: focuses on the risks inherent to the use of batteries in both mobility and stationary applications.

Battery systems are developed for integration into existing systems, including vehicles and infrastructures in case of BESS. Therefore, it is necessary to ensure that these new technologies do not increase the risk for individuals and society beyond the common Risk Acceptance Criteria at national level. There is a need to develop safety cases to ensure compliance with the local regulations which would require the performance of Quantitative Risk Assessment (QRA) (e.g. BESS QRA).

The main risks associated with using battery systems are possible fire and explosion hazards, electrical hazards as well as chemical leakages. All of which can have a dramatic effect both on the users, the environment and infrastructure. These risks are applicable to both stationary and mobile applications, however, the mechanism of occurrence of a risk may be different depending on the use-case. Therefore, it is essential to understand the actual use-case when designing the cells/packs/systems for a specific application (from interactions with other components in the system to possible external hazards).

4.2 Mitigation, Prevention Actions and R&D Needs and Challenges: details strategies and actions to counteract risks in the use phase

4.2.1 General approach to improve the application safety

First of all, there is a need to develop consequence modelling tools at BESS level to evaluate potential impact on infrastructures, considering both private and public buildings. Further research is required to enhance the understanding of the TR spreading process and external hazardous consequences, specifically concerning heat fluxes, overpressure and toxicity.

Regarding the risk prevention approach, it is necessary that the final product FMEA is verified for the selected application: for example, verification that the expected operating condition do not exceed the design capability associated to the real manufacturing level of quality, over the product life duration. Such a study should also include the risks associated with the interruption of the application service due to a battery failure and mitigate the potential consequences, when needed.

In terms of the risk mitigation approach, it is necessary that the foreseeable abuse conditions in the application are reviewed in order to assess the potential hazards and the consequences at the application level. The risk should be assessed (including existing mitigation means for the selected cells and batteries) and decision about the need of additional mitigation means at the application level should be clarified. The development of a general hazard-based classification system (like the undergoing UN classification for transport and EUCAR for e-mobility) and safety KPIs for EES would give clarity on this regard. However, conducting comprehensive studies that extensively describe the

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safety levels of different cell types would be beneficial in aiding the selection of the appropriate cell type for a specific application.

Similar to Oil & Gas (OIR 12) or more recently for hydrogen activities (e.g. HIAD), it is necessary to develop a battery failure frequency database at the European level. The first step is to develop a common database structure that covers various battery scales or applications, including EV and BESS. The structure should be capable of capturing the incident's description, potential root causes, and the consequences for people, assets, and the environment. The development of EV and BESS fire incident registry and standardised reporting procedures could significantly improve the understanding of the fire risk. The second step is to provide the database to various stakeholders who will provide the data from incidents in an anonymised and secure manner. Once the sample size is sufficient, this will enable the calculation of failure frequencies for cells, units, etc., which will be valuable for further risk assessment.

The safety tests of LIBs for major applications are described by the corresponding standards. Specific material properties help to enhance the intrinsic safety of LIBs considerably, although a thorough trade-off between required safety, costs and performance should be made for every singular application (e-mobility, stationary, consumer, maritime etc.). As described in the Chapters above (chapters 2-3), several measures at the material and cell level can improve the safety of BESS. For safety at the battery pack and system level these safety features are initially made use of and employed for their application specific practical implementation.

4.2.2 Safety at laboratory level

Testing large batteries in a laboratory is less common than for cells because it involves higher costs, adapted test devices and can turn out to be dangerous if the test sample is defective, unintentionally abused or if an unforeseen issue occurs with the device or the electric grid. In this respect, virtual testing, based on models and simulation tools as well as verification of the electronic safety systems is a prospect for further development.

4.2.3 Stationary electrical energy storage systems

Stationary EES often are very high energy applications. Also, they are more and more often installed in private households for photovoltaic applications (see Annex V of regulation 2023/1542). It must be secured to prevent fire, explosion, high temperatures, toxic and explosive gas emission, propagation to neighbouring areas as well as high voltage and chemical spilling dangers. To this aim the development of risk assessment methods is considered as a high priority: risk assessment shall target the environment, especially the risk to human life. This includes methods for risk assessment, minimum safety requirements for the validation of the safety measures and for their monitoring throughout the lifetime for stationary EES systems. Mitigation and prevention measures need to be developed for the different scenarios. These need to be transferred into standards and regulations, which still need to be further developed. Also, key performance (digital) indicators (KPI) for safety need to be defined.

In case of fire and/or explosion in stationary storage systems it is necessary to define action procedures: common European standards for emergency should be defined as well as unambiguous

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guidelines for the use of suitable extinguishing media based on the results of experimental testing and models. Emergency Action Plans are especially needed for the end-users, fire brigades, first responders and emergency personnel. It is also important to define safety measures regarding to connections and interfaces to the power grid, and to provide guideline in order to facilitate the safe handling of battery packs and cells under normal and emergency conditions. Up to now only Seveso-III Directive (Directive 2012/18/EU) on the control of major-accident hazards involving dangerous substances provides for the relevant framework on risk management measures to prevent major accidents and to limit their consequences.

Redox-flow technology is also extremely relevant for large-scale stationary energy storage (e.g., C&I and utility-scale) due to techno-economic considerations. Redox-flow batteries are energy storage systems in which the energy is stored in liquids or in a liquid and gas. Among battery technology alternatives, RFBs appear best suited for long-duration energy storage stretching from 8 hours to seasonal storage. The main appeal of flow batteries is the decoupling of power rating and energy capacity enabled by the spatial separation of the electrochemical stacks and the electrolyte tanks. This feature has significant fire safety benefits too. When a flow battery is in operation, typically only 1% of the electrolyte volume is contained in the cell stack while the rest resides in the bulk electrolyte tanks. Despite great fire safety performances of most flow batteries[15], the main safety concern in RFB technologies is electrolyte leakage and spills given the extensive plumbing system that characterise this type of batteries. Some RFB chemistries utilise highly corrosive acidic and alkaline electrolytes such as concentrated sulfuric acid and potassium hydroxide solutions respectively.

Additionally, some of the electrolytes are toxic. As a result, a potential leakage presents a high risk of contamination for water sources, air and soils. Electrolyte leakage and spills are mitigated by employing secondary and tertiary containment which creates a closed system thereby preventing electrolytes from escaping from the reservoirs and mitigates the effects of leaks along pipe segments. The establishment of the International Flow Battery Forum (IFBF) in 2010 provided a major boost to the advancement of RFB safety codes in Europe. Three IEC codes are dedicated to RFBs have been published in 2020 addressing terminology and general aspects, performance and testing conditions and safety requirements[16]. While risk associated with commercially available solutions such as Vanadium Flow Batteries and Zinc-Bromine RFBs have been analysed in more detail[17], safety studies of RFBs technologies that are currently under development or upscaling is needed to address potential issues.

4.2.4 Transport systems

Contrary to the stationary EES, for EES in transport many regulations and a number of standards are available[11,18,] . However, specific approaches for specific applications are needed, e.g. heavy duty EVs, maritime applications and aeronautical applications.

In practice, in the transport area two scenarios can be identified as especially safety relevant, i.e. charging process and mechanical damage. As charging (especially fast and ultra-fast charging) is one of the critical phases of using LIBs in EVs, safety rules need to be developed on the basis of testing and the acquired knowledge from developed experiments. For example, safe designs of fast and ultra-fast charging stations shall be identified. For low power charging, a redundant monitoring of end of charge and thermal conditions are needed. As mechanical damages and crashes are the other main cause of

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EVs accidents involving battery fires, designing of crash-proof housings or structures to absorb impact energy is important. Another possibility to increase safety in a crash is to limit the damage to the affected cells / packs and to avoid propagation to the other areas, e.g. by cooling or by constructional measures. In case of a vehicle accident, it is necessary to define action procedures to be implemented into existing European standards for emergency services and tow trucks for the safe extinguishing, removal, handling, transport and disposal of damaged batteries.

Furthermore, warning instruments for the driver, providing action plans, offering self-dialling for communication with emergency numbers and other, could be further developed and implemented. Finally, for all applications, improvement of safety is closely correlated to understanding the causes and processes of TR. Real-time tests with EES on the reality scale are needed to obtain further information, as simple up-scaling of results from the cell level may not deliver correct results. Therefore, models with input data on cell, pack and system level are needed[19]. Testing should include the different methods of initiating the TR event as well as propagation tests. Also, the effectiveness of TR preventing measures (BMS, thermal management, use of protected cells, CID, PTC, flame retardants etc.) need to be proven by testing to confirm models results. Data from respective research projects should be merged in a database and become available for the use in models. These models will serve to reduce testing efforts as more data will become available.

4.2.5 1st and 2nd life

In the manufacturing process, as well as for recyclability and 2nd life use of cells or batteries, it is essential to know the state of the battery pack as well as of each individual cell. Besides the State of Health (SoH) and the State of Charge (SoC) especially the State of Safety (SoS) is important to decide about the continued use of a battery. 1st life SoS may be differ from the SoS of the 2nd life. The SoS from 1st life might not be applicable in applications using 2nd life batteries. Research needs to be performed on aged cells both in 1st and 2nd life to understand how these boundaries are changed with aging. For example, in a crashed EV, when it is known that not all but the affected cells of the battery are still safe for use, they can be reused or adopted for a 2nd life application. This will enhance the service time of cells and therefore preserve environment and resources. It is essential to identify suitable parameters and to develop new non-destructive testing (NDT) methods for SoX diagnosis of the cell. Especially NDT methods for SoS cell diagnosis are missing to date. In addition, for verification of the compliance with safety testing requirements before second-use, schemes for selective testing must be developed, as not each cell in a large battery can be tested.

4.2.6 Safety systems

In the perspective of developing probabilistic event trees, it is necessary to consider the reliability of safety systems. For the electronic parts (e.g. BMS), there is a strong available knowledge to calculate Safety Integration Level (SIL) but it should be related for other safety systems such as extinguishing systems, ventilation, etc.).

In parallel, supercomputers working on innovative quantum chemical calculations is crucial for the competitiveness of Europe and member countries regarding the next-generation of battery electrodes. Quantum computing has the potential to revolutionize how fast calculations can be performed, which

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will have positive implications on whole value battery chain, therefore protection of knowledge is needed in terms of cybersecurity strategies. The risks linked to cyber security, an increasing concern due to the ever-going digitalisation and digital integration of battery-based systems, either standalone or in which batteries are a key part, should explicitly be taken into account. Specific measures and procedures should be developed, implemented and updated as necessary to follow the evolution of digital protocols and operating modes[20].

4.2.7 Emergency response

In general, during the implementation of a battery as a product, various barriers are investigated throughout the engineering process to mitigate the risk of potential losses (people, assets, etc.) arising from identified hazardous situations to achieve a risk configuration As Low as Reasonably Practicable (ALARP), as shown below on *Figure 5.*

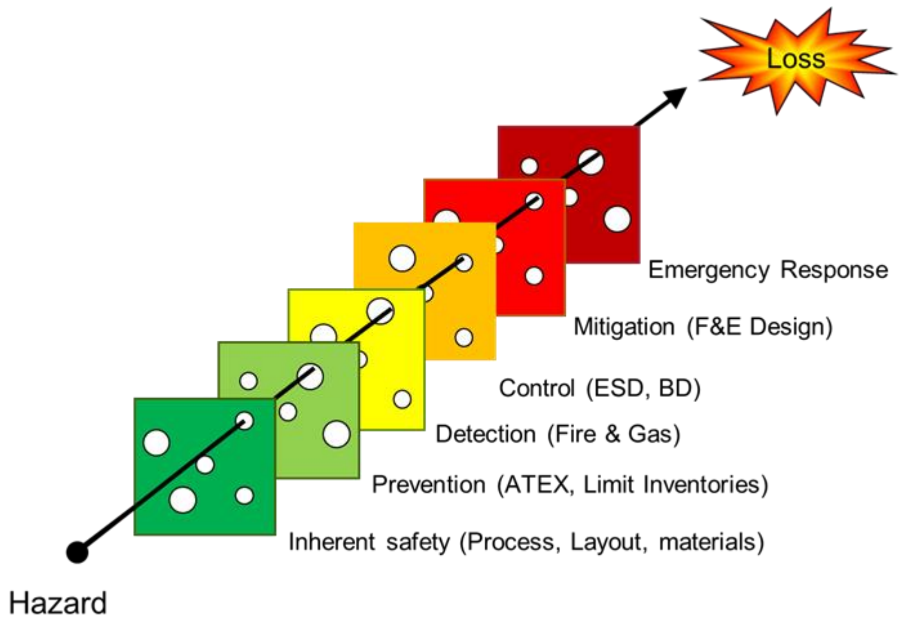

Figure 5: Process safety Management ALARP describes the level to which a risk is expected to be controlled.[21]

Even though inherent safety is a primary consideration during the design phase, additional Risk Reduction Measures (RRM) involving prevention, detection, control and mitigation are typically incorporated. Emergency response measures such as evacuation of people, remains the ultimate option.

Firefighters face multiple challenges when addressing battery fires in enclosed spaces, such as managing stranded energy, potential explosion hazards, toxic gas exposure, prolonged extinguishing operations, large water use, the risk of battery re-ignition, and the handling of the post-fire battery and contaminated water. Despite warnings from OEMs, firefighters are exploring direct methods such as cutting extinguishers and piercing devices, which have shown effectiveness in cooling fires and reducing water usage. Nevertheless, studies have shown that the environmental impact is higher when

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using such methods. More research is needed to determine which tactic is best from several perspectives: time of operation, risk for fire spread, environmental impact, and handling of stranded energy. It is necessary to develop technical solutions and clear recommendations to improve firefighters' emergency responses.

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5 SAFETY IN END OF LIFE

5.1 Hazard Sources: addresses the potential hazards associated with the disposal and end-of-life treatment of batteries.

The handling, storage, dismantling and transport of waste batteries involves the same main areas of electrical hazards, fire and explosion hazards and chemical hazards as described in the previous chapters. In addition, the recycling processes, including mechanical, thermal and chemical pre-treatment, introduce new interrelated hazards.

A specific analysis is required for the identification of the hazards in the waste batteries flows, which will vary depending on the origin, the composition and the liability to react during treatment of the mixed waste batteries.

5.2 Mitigation, Prevention Actions and R&D Needs and Challenges: discusses measures for safe handling of batteries at the end of their life cycle.

5.2.1 Recycling

Used battery packs, module and cells should not be put to recycling bins, instead they should be taken to certified battery recyclers or special battery terminals. This requirement is also a part of the Battery Regulation mentioned earlier. An important focus point is how to enable the safe disassembly of the battery/pack into the individual cells, if a battery cannot be reused as a whole. For the process of disassembling - in a recycling company as well as in an emergency e.g. after an accident - straightforward methods for diagnosis need to be available. To ensure the safety of battery recycling, the following precautions should be taken: handling precautions, disposal options, specific guidelines, awareness, and education. By following safety precautions, the risks associated with battery recycling, such as fires and environmental harm, can be minimised. Furthermore, availability of information on product design and safety for emergency workers on scene (especially for the EV market) is needed. Following topics for enhancement of safety in recycling are important: a) the development of fast testing/diagnosis of SoX of a battery is needed. An economically viable solution would require fully automated identification of reusable cells; b) the creation of a database containing safety relevant data on EES should be developed in order to support safe recyclability; c) the increase in occupational safety by disassembling batteries into cells with robots and employing artificial intelligence.

To increase the safety during handling, the battery can be discharged/deactivated (salted water immersion, cooling or freezing etc.) before the handling to minimize risks like TR or electrical shock. For the design of such processes a good understanding of the underlying mechanisms is required. Support of the battery manufacturer is needed in order to create a standard procedure for safe dismantling and recycling of a specific battery. The manufacturers are now required by the European Battery Regulation to ensure access to relevant data. This should ensure more knowledge on related safety-measures is available for the recyclers. Specific education of the operator is important to ensure safety of the process. The development of and automatised process utilising also robotic applications for disassembly can broaden **the reuse of cells for 2nd life** in stationary applications.

The mitigation measures in case of an incident during recycling should include the scenarios of potentials hazards resulting from abused cells (chemicals release, gas release, flames etc.) as the cells' composition for recycling flows is potentially less under control.

5.2.2 Sustainability

The safety and sustainability of batteries are closely related, as both aspects are crucial for minimising environmental impact and ensuring the responsible use of resources. Battery recycling is the preferred action in order to minimise environmental harm and can lead to advancements in more eco-friendly and circular future battery manufacturing. A life cycle thinking approach for the material/cell/system innovation landscape includes the evaluation of safe-and-sustainable-by-design parameters covering safety, environmental, social, and economic impacts. Exploring ways of reducing side effects on the environment and ensuring batteries do not pose a danger to the health of workers or users must be in priority in massive deployment of battery sector. There is also indirect influence on water quality at sites of mining, manufacturing batteries at gigafactories and giga-recycling facilities etc. Sustainable and safe batteries are common inquiries coming from latest climatic policy on the way to achieve the critical material security goals set by battery industry strategy. It goes hand in hand with public awareness and trust into emerging battery technology in general.

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6 SAFETY TESTING

Battery testing covers the areas of performance, aging, and safety. Testing is inevitable to validate the safety of a system. There is quite a number of testing instructions regarding the safety for EES applications, most of them in the automotive sector, but only a limited number of regulations containing specific testing requirements. Some common testing standards and methods include IEC 62619, IEC 62133, UL 9540A, UL 1973, UL 1642. Battery transport is regulated by UN and regional and national legislations. The most important regulation is the so called 38.3 tests (UN Recommendations, Handbook of tests and criteria) which is a prerequisite for transport of LIBs and therefore for putting them to the market. Tests are done both at cell and battery/system levels. The second major regulation is the ECE homologation for the approval of vehicles and vehicle parts (R 100) and is mandatory in Europe since 2016, which is necessary but not sufficient. Tests are done at cell and system level.

In addition, there are several specific standards and requirements (ISO, SAE, UL) that are very disparate depending on the sector. They cover safety and test aspects from the areas of thermal, electrical and mechanical abuse. Contrary to automotive, in other sectors like stationary storage, reuse, or warehouse storage the standards are underdeveloped. As keeping an overview is difficult and existing standards are not really consistent, the development of a general standard (base) usable in a broad range of application should be supported. Specific requirements for special application can be foreseen.

Two major challenges are nowadays existing in the field: a) while creating or updating an existing standard or procedure: What test procedure can be used? / What criteria need to be considered? b) while putting a new battery on the market: Where can those tests be performed (especially at large scale)?

6.1 Test procedure

Safety test requirements are different according to the field they cover, and tests procedures are adapted to the need. Improvement of a test procedure increasing its suitability and decreasing the test duration can allow for smoother industrial uptake of the procedures and, therefore, improve the safety of LIBs overall. A critical review of safety testing methods on cell and battery levels would be of great interest**.** This task requires extensive work and is out of scope of this document. However, some issues or shortcomings are common to most fields:

- Material safety evaluation: different tests can be used to test safety of materials, for example, calorimetry. The development of a safety assessment methodology for battery materials is needed to cover the relevant fire scenarios (internal vs external).
- TR initiation.

To initiate a TR several methods are possible and needed depending on the level and the purpose of the test. Methods include but are not limited to: thermal abuse, nail penetration, internal short circuit, overcharge and laser puncture, combined with advanced characterization techniques. Each of the methods has its own advantages and drawbacks.

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Research on the parameters influencing the severity of the test and thus the outcome, would be useful. Development of test methods or protocols that are reproducible, non-invasive, do not impede more stable technologies and are usable in a wide range of battery architecture would help in the development of many standards and in the evaluation of battery safety. Particularly, the development of European standards is needed. AI tools, as well as physics-based models will increase the understanding and predictability of thermal runaway state initialisation.

6.1.1 Evaluation of hazards resulting from a battery during thermal runaway

When a battery enters in TR, several hazards might be produced: emission of toxic gas, heat, fire, projections. It is essential to be able to evaluate those hazards and define requirements in European standards and regulations. For well-defined conditions some hazards, like fire or projections, are easy to evaluate. However, others hazard, like heat or gas emission are very difficult to assess and extensive work has to be conducted in this area. For example, at cell and module level, standard conditions should be stated in order to make comparison possible between different batteries and technologies. This work could be profitable in most applications and lead to a real safety benefit for every user. It would also greatly support the safety assessment of new technologies.

6.1.2 State of safety of a battery (SoS)

All along its use a battery will evolve, not only in terms of performance (SoH) but also in terms of safety. Many tools have been developed to evaluate the SoH and are imbedded in the BMS (impedance, capacity evolution etc.). Developing tools to evaluate SoS would not only improve safety of use but would help the selection of (safe) cells for 2nd life application, ensuring safety.

6.1.3 Representativeness of tested batteries

A good safety test should be reproducible, and representative for commercialised batteries. Aiming toward this effort, standards can define a “type” of batteries that is covered by a certain test realised. The battery type defines the changes acceptable (in energy, architecture etc.) of the battery ensuring the reliability of the test and thus the validity of the certificate. Within a battery type, uniformity in behaviour is ensured by quality insurance and control during fabrication at every level (material, cell, system). This quality insurance is almost impossible to introduce for used batteries since their “properties” will depend on how they have been used. This point is very important for 2nd life applications and is closely tied to the SoS. If the definition of a battery “type” is not possible the test could be performed on a “worst-case battery”. IEC 63330 standard proposal is under preparation and its purpose is to provide basic requirements for the application of repurposed lithium products, mainly targeting lithium batteries, but not exclusively. This standard aims to increase knowledge sharing and the capacity of countries to apply IEC work to address national ESG (Environmental, Social, and Governance) issues.

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6.1.4 Accidental response and environmental impact

In case of an incident, a battery system might leak or even produce intense heat and fire. An isolated incident at the cell level might propagate to the whole system or even to adjacent systems. To avoid severe, extended incidents, passive and active mitigation systems are developed to break the propagation chain. Appropriate passive fire protection, such as fire rated walls should be adapted to each individual risk. Various extinguishing agents have been developed for LIBs and can be used depending on the technology (different agents may be needed for Li-metal and Li-ion, respectively). They can take the form of a liquid, a powder, a gas or a mixture of them. Evaluation of the efficiency of those agents is very important to improve mitigation systems and to help first responders to choose the right extinguishing medium.

Study of the toxicity and environmental impact of the emitted liquids, fumes, soot and discharged extinguishing water is useful for post accidental crisis management. In order to evaluate the environmental effects of possible leakages, aquatic ecotoxicity tests (Daphnia, Alga, Bacteria) of the water leachates following OECD procedures can be carried out[22].

6.2 Demand for testing and facility capacities

Expected increase of cell production and EV market size at European level will increase demand for testing capacities. A reduction in test duration and costs is crucial to allow a fast market access and increase Europe's competitiveness.

In addition to this increase in demand, large-scale testing is done by only few laboratories in Europe leading to long waiting times, hence slowing down industry development agendas. To solve this problem, several solutions can be considered:

- Improve guidance on selection of the laboratories and test procedures by developing and listing European standards and listing certified laboratories that can cover them in each country;
- Adjust the standard procedures to make them more efficient and robust;
- Develop models to predict large scale test results based on real test at smaller scale. In order to develop and calculate successful models, numerous key data will be required. A database continuously extended with new test results would help to significantly improve models.

The development of European network of laboratories, capable of running internationally accepted standardised measurement within an ISO 17025 accredited process can also help to improve the efficiency of the safety testing sector and the development of harmonized test protocols (fair and equivalent tests). In a general overview, education of technician working at different level of the circular battery value chain is necessary to properly handle batteries, recognising and avoiding dangerous situations.

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7 CONCLUSIONS

Both commercially widespread LIBs and newly emerging battery technologies are still perceived by society as being potentially dangerous. The publicly reported accidents (that are sometimes spectacular) and the related media coverage is causing more safety concerns amongst general public. However, it is essential to note that today's **battery systems have already reached a good level of safety.** With the increase in size and specific energy of the batteries for e-mobility and the introduction of batteries in smart grids like net-boosters, there is a demand for continuous improvement of advanced safety solutions. Substantial efforts at different system levels to detect and mitigate possible hazards have been taken. Further improvements, in particular those impacting the safety at the material and cell levels (intrinsic safety) will reduce cost and effort at system and application level. Also, it is possible to develop advanced safety approaches at the battery pack or even at system level. In this regard, this document has presented a comprehensive review of the challenges on the cross-cutting topic 'Safety' along the whole battery value chain.

New battery technologies may result in major improvements in safety and there is already a lot of research done in this direction today, and for this the safety assessment for materials and their compatibility should become a part of every new material development. At the same time, novel materials or technologies of future battery generations could bring new hazards which should be considered. Together with this, research activities such as self-healing and/or sensing at material/cell level may help to improve safety or prevent against accidental scenarios. In addition, novel designs for future technologies should include the global FMEA analysis and the identification of the prevention and mitigation means applicable at cell level. **Sensing technologies** have been recognised for their benefits in various fields for decades. In the context of batteries, the ability to monitor and gather data on chemical, thermal, and mechanical parameters will be crucial for ensuring safe and efficient operation. **Robotics and the automatization** of processes is clearly seen as a key action for several parts of the battery value chain such as manufacturing, handling, transport, recycling and storage of waste and damaged or defective batteries. Automatization of processes should be designed to improve the outcome of the processes and tests avoiding human interaction and decrease the test duration. In this regard, together with automatization and robotics **digitalisation** is essential. Research and development are needed to provide digital safety tools, simulation and modelling at all levels, in order to achieve the high level of safety that is needed for the acceptance and increased use of EES. In addition, the development and setting of **safety key performance indicators** (KPI) would be very beneficial. Both actions would increase safety of LIBs and reduce the time-to-market. To achieve that goal the **standardisation** of those processes is crucial. At pack and application level, many efforts have already been taken, which should be improved to eliminate shortcomings and missing aspects. It has been highlighted that the creation, and improvement of safety standards along the full battery value chain levels, will help to develop quicker, safer and greener battery technologies.

Second life applications and the extension of life of used batteries are one of the green solutions that is being tackled. In this field, there is a need to develop the adequate tools to select the reusable batteries and to manage the new associated risks. As a clear example, methods for SoS cell diagnosis are missing to date. Only those used batteries may go into a 2nd life application which still have the appropriate safety level which also still needs to be defined as a KPI. All in all, becoming a **"greener",**

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safer and more sustainable society includes, as described in this report, many technical challenges. Therefore, **education** in the wide battery field is an important topic to discuss at all professional levels.

For **battery testing,** specific risks have been identified at laboratory level, such as chemical and fire hazards. In this regard, a general laboratory best practice report is needed for educational and professional purposes. In addition, testing large batteries in a laboratory is often not practical instead of cell testing because it involves higher costs, adapted test devices and comprises higher dangers. Testing should be complemented by **safety models, simulations tools** and safety guidelines for all, academic, technical and user profiles.

Figure 6: Safety in the Circular Battery Value Chain[23]

Safety needs to be considered from the **whole battery value chain perspective.** It is clear that the improvement of safety at any specific level of the value chain, for example at the material level, will be beneficial for all levels. Safety does not only embrace the safety of the final product during its intended use, but also from a life cycle assessment approach. As the figure above indicates, safety must be considered in a much broader scope including:

- material handling, components processing, cells, modules and system manufacturing/assembly, installation of battery systems;
- use, maintenance, repair and second life of the product in its application environment;
- dismantling, handling, transport and storage of waste, damaged and defective batteries.

It is undeniable that safety actions should have a stronger role at all steps within the battery value chain to align the different steps and create a faster, safer and more sustainable market introduction of current and new generation batteries in Europe.

Education and training as key (see also Task Force Education & Skills position paper)

Finally, there is a high demand and need to prepare well-trained future hybrid engineers with advanced skills on safety of batteries, used chemicals, materials, processes via participation on dedicated courses on Safety of batteries under umbrella of European Battery Academy lead by R&D experts working on safety. EIT InnoEnergy Skill Institute launched first on-line courses on safety in manufacturing and

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recycling of batteries[24]. There is an opportunity to prepare also a joint master and PhD degree programmes under European Networks of Universities.

The complex designs and rapid increase in types of battery technologies require a workforce that can understand the risks, adapt as necessary to new risks, and respond when it counts most. LIBs unlock great opportunities for the clean energy transition but also come with the rare but serious risks of battery fires and explosions. For instance, the incident in the French warehouse in January 202325 or the Dutch cargo ship in July 2023[26]. Battery fires are a risk for consumers as well, as the Tesla fires after Hurricane Idalia in Florida in September 2023[27], and firefighters often lack the training to handle these types of fires. It is possible that incidents like these could have been prevented with broad safety training, leaders who oversee its implementation, and a culture of safety. Battery fire risks are on top of other inherent risks when working with batteries, such as electrical shock or exposure to hazardous chemicals.

A general-purpose battery safety compliance training opens a new angle for us to enter existing markets. There is not standard or widely available training for companies to remain compliant with battery safety standards set by regulating bodies like the United States' Occupational Health and Safety Administration (OSHA) or the European Agency for Safety and Health at work (EU-OSHA). While companies are naturally concerned with reducing the number of safety incidents, their primary motivation lies in maintaining compliance with regulatory bodies. The most common tactic companies use to address these training needs is to build proprietary training content, either in-house or contracted out to a 3rd party. Otherwise, they may rely on hiring workers who already have this knowledge or providing informal on-the-job training in these areas.

InnoEnergy's positioning and industry visibility across the value chain can offer a competitive support to contribute in Education and Training regarding Safety, serving as the connecting point between industry needs and the knowledge transfer offer from more academic partners/stakeholders.

As an upsell for the safety compliance training, we can offer complete training for safety officers. Employing a safety officer at every stage of the battery value chain can prevent disasters and spread awareness of the basic safety procedures outlined in the compliance training to all relevant workers. This crucial role also has the skills to analyse battery risks and report on battery incidents if they happen. They are also responsible for mitigating other risks in the plant, such as injury risks from heavy equipment or manufacturing machinery. Spotlighting this important role further solidifies InnoEnergy's commitment to safety and supports the general battery safety compliance offering.

This project has received funding from the European Union's Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

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This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676

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Batteries Europe

Position paper

Sustainability
Task Force

April 2024

In cooperation with

BEPA
Batteries European
Partnership Association

ACKNOWLEDGEMENT

Batteries Europe Secretariat is an EU-funded project that has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676.

DISCLAIMER

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Acknowledgements: We would like to thank Spyridon Pantelis (EERA) for the overall coordination of the Task Forces, Alessandro Romanello (EIT InnoEnergy) as coordinator of Batteries Europe, and the BEPA Secretariat for their support in the operation of the Task Force. Special thanks to Fatima Ahmed, Adeola Adeoti, Lucia Sardone (CLERENS), and Maria Luisa Fernandez Vanoni (EERA) for editorial support. We would also like to acknowledge the inputs and considerations from the European Commission, the Batteries Europe Secretariat and Batteries Europe Advisory Board.

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676

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Research and Innovation Programme under Grant Agreement N. 101069676

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ABBREVIATIONS AND ACRONYMS

Abbreviation	Definition
B2B	Business to Business
B2C	Business to Consumer
BAT	Best Available Technology
BMA	Battery Management System
BMS	Battery Management System
CAPEX	Capital Expenditure
CO2	Carbon Dioxide
CRM	Critical Raw Materials
CRMA	Critical raw Materials Act
DPP	Digital Passport Product
EoL	End of Life
EPA	Environmental Protection Agency
ESS	Energy Storage System
EV	Electric Vehicles
FEP	Fluorinated ethylene propylene
FKM	Fluoroelastomer
GC-MS	Gas Chromatography-Mass Spectrometry
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GWP	Global Warning Potential
ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LC-MS	Liquid Chromatography-Mass Spectrometry
LCOS	Levelized Cost of Storage
LFP	Lithium Iron Phosphate
LIB	Lithium-Ion Batteries
LMT	Light Means of Transport batteries
MCDA	Multi Criteria Decision Analysis
NMC	Lithium Nickel Manganese Cobalt oxide
NOX/SOx	Nitrogen/Sulfur Oxides
NZIA	Net Zero Industry Act
OECD	Organization for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
PBT	Polybutylene terephthalate
PCR	Product Category Rules
PEF	Product Environmental Footprint

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PEFCR	Product Environmental Footprint Category Rules
PEI	Polyethylenimine
PFA	Perfluoroalkoxy polymer
PFAS	Per- and polyfluoroalkyl substances
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
PLC	Polymers of Low Concern
Post-LIBs	Post Li ion Batteries
PPS	Polyphenylene sulfide
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RFB	Redox Flow Batteries
SBM	Sustainable Business Model
SETAC	Society for Environmental Toxicology and Chemistry
SLB	Second Life Battery
SLCA	Social Life Cycle Assessment
S-LCA	Social Life Cycle Assessment
SLI	Starting, Lighting, and Ignition
SOC	State of Charge
SOH	State of Healthy
SSbD	Safe and Sustainable by Design
TRL	Technology readiness Level
UNEP	United Nations Environment Programme
VDF-HFP	Vinylidene fluoride-co-Hexafluoropropylene

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Research and Innovation Programme under Grant Agreement N. 101069676

Executive Summary

Three years after the first position paper of the Task Force Sustainability[1] this updated position paper aims to take a comprehensive look at the sustainability of present and emerging batteries and the entire value chain, including the framing conditions. It also explores how this fast-growing sector can foster an innovative environment and develop a more sustainable battery ecosystem, considering the importance of recycling, second use, and the circular economy. Three key dimensions of sustainability are in focus: economic, social and environmental sustainability, especially from a life cycle perspective. Furthermore, the paper reflects on EU regulations and related activities such as the "*Net-Zero Industry Act*," the "*Critical Raw Materials Act*" (CRMA), and "*Safe and Sustainable by Design*" (SSbD) as framing conditions.

The Batteries Directive (including the Battery Passport) already covers important sustainability aspects over the entire value chain for present batteries (i.e. LIBs), with challenging minimum recycling rates and recycling content in batteries in the future. However, there is the urgent need to expand the digital passport to all battery types. This will require the development of a comprehensive framework for the environmental assessment also of alternative battery technologies and their second life use.

The main benefit of Second Life Batteries (SLB) lies on their environmental performance, since they are not burdened with the impacts related to the first life battery manufacturing. On the other hand, the application of SLB is challenging as it still comes with various uncertainties from a business perspective. Research is therefore needed to address the potential of the batteries reaching the second life use in terms of performance, as well as cost and economic viability of using SLB instead of LIBs.

The ongoing discussion regarding per- and polyfluoroalkyl substances (PFAS) and the usage of critical raw materials in the case of lithium batteries highlights the importance of recycling and circular economy. Additionally, the low economic value of used materials in post-lithium batteries (such as sodium-ion batteries) creates foreseeable challenges that need to be urgently addressed. Therefore, activities regarding "*design for recycling*" and first attempts towards direct recycling are promising options to overcome these challenges.

1 INTRODUCTION

1.1 Scope

The availability of abundant, affordable, renewable energy, generated with little or no environmental impact, particularly in terms of carbon emissions, is one of the cornerstones of any advanced and sustainable economy. Both current and future renewable energy sources will primarily rely on wind and solar energy, which are by nature intermittent and strongly dependent on local climatic conditions. This creates challenges for ensuring a consistent and reliable energy supply to people and industry, as there will naturally be imbalances between supply and demand. One of the most suitable approaches to overcoming these challenges is to store excess renewable energy when there is a surplus and use it when the production of renewable electricity is low, thus balancing the grid and improving the competitiveness and efficiency of renewable energy systems.

Even though the most suitable energy storage option depends on the specific application conditions and local/regional constraints, batteries are often the most sustainable choice when compared with other options. For transportation purposes, especially in the case of automobiles, batteries offer much higher energy efficiency and safety compared to hydrogen [2]. Moreover, batteries are versatile and easy to use, with various technologies and chemistries available to suit different needs. For example, Vanadium Redox Flow Batteries are a suitable option for stationary energy storage, whether on a large scale or domestic level, due to their longevity, minimal energy losses, safety, and adjustable storage capacity. Additionally, batteries come in a wide range of sizes and shapes, from small button batteries used in electronic devices to large batteries used for grid stabilisation. Existing commercial batteries are robust enough to integrate into renewable energy systems, particularly in residential or decentralised setups, thereby promoting sustainability at local level. In industry, batteries play a vital role in increasing process electrification by providing a steady energy supply to equipment or supplying heat. Another potential application in the chemical industry involves the increased utilisation of electrochemical-based processes, where electricity serves as a reactant.

Batteries have a fundamental role to play in the shift towards cleaner mobility and energy systems, contributing to the CO_2 reduction targets established by the UN COP 21 conference in Paris[3]. However, sustainability encompasses more than just reducing the environmental impacts and carbon emissions. It includes the mitigation of atmospheric pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO) and particulate matter (PM), as well as the greenhouse gases (GHG) responsible for climate change, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), in addition to reducing water and soil pollution, preserving landscapes and biodiversity, waste management and the efficient use of clean renewable energies. Ensuring the safety of workers from hazardous substances and maintaining fair labour conditions and wages are also crucial components of sustainability. Economic stability and geopolitical independence are additional vital aspects.

Current Lithium-Ion Batteries (LIBs) face various sustainability challenges across all three pillars of sustainability (i.e. economic, environmental and social). For instance, their reliance on critical raw materials like Cobalt (Co), Lithium (Li), and Phosphorous (P), their high environmental and social impacts during production, high overall production and life cycle costs, the need for technical performance enhancements, complex and costly recycling processes, safety issues across production,

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usage, and recycling stages, and inadequate traceability (e.g. of material chemistry, battery life, etc.) along the value chain.

Future post-lithium battery systems (post-LIBs), (e.g. Na-Ion, Mg-Ion, Ca-Ion,) and other emerging systems like Redox Flow battery (RFB), such as Vanadium or Iron-based, must overcome present challenges from both a battery performance and sustainability perspective. This is certainly not an easy mission and can only be achieved through multi- and interdisciplinary research.

In that respect, this paper provides a comprehensive overview at the present sustainability challenges of the battery value chain and suggests recommendations on how Europe can foster a thriving environment for a more sustainable and circular battery production and business ecosystem. Its main focus lies on the three main sustainability areas, namely, economic, social, and environmental, which should be addressed together in order to enable a more sustainable battery sector.

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2 Overview of Regulatory Frameworks

In 2022 and 2023, there was a substantial increase in discussions on new proposals by the European Commission aimed not only at enhancing the competitiveness of the European battery industry but also at ensuring its sustainability. The European Union has launched different initiatives and approved various directives and regulations with the goal of making the European Union's economy more sustainable with the overall aim of achieving net-zero greenhouse gas emissions by 2050, boost the efficient use of resources, and restore biodiversity, while at the same time improving the welfare of its citizens[4-8]. The Green Deal Industrial Plan is part of these initiatives, and it is specifically focused on ensuring that Europe's industry can transition to a sustainable and digital future while remaining competitive at global scale. This plan included three initiatives: the Net Zero Industry Act (NZIA)[4], the Critical Raw Materials Act (CRMA)[5] and reform of electricity market design[6]. Directly related to the issues of raw materials, the EU Conflict Minerals Regulation[7] can also be relevant. Additionally, the EU has ultimately adopted the updated Batteries Regulation[8], including crucial provisions on the battery passport and carbon footprint declaration, the 'safe and sustainable by design' (SSbD) framework [9] and initiated a comprehensive analysis of a large class of synthetic chemicals — per- and polyfluoroalkyl substances (PFAS)[10]. All these approaches will have a significant impact on battery sustainability.

2.1 Batteries Regulation

In 2020, the European Commission presented the proposal for the revision of the Batteries Directive (2006/66/EC). After two years of consultations and negotiations, a final agreement was reached in December 2022. The updated Batteries Regulation (EU/2023/1542) encompasses a legislative framework aimed at ensuring the environmental sustainability of batteries. It covers the entire life cycle, from raw material extraction, manufacture, distribution and use, to waste management, disposal or recycling of batteries placed in the European market.

In July 2023, the European Parliament approved the updated regulation regarding batteries and waste batteries that should prevent and reduce the adverse impacts of batteries on the environment and ensure a safe and sustainable battery value chain for all batteries. This considering, for instance, not only the technical requirements, but also the battery's carbon footprint throughout its life cycle, ethical sourcing of raw materials and security of supply and facilitating re-use, repurposing and recycling.

This regulation specifies rules from a technological and environmental perspectives. It defines responsibilities of stakeholders along the battery value chain and includes detailed information and rules to ensure that batteries meet the defined requirements. It also defines the types of batteries that should be subject to its requirements, including: electric vehicle batteries, light means of transport (LMT) batteries, portable batteries, starting, lighting and ignition (SLI) batteries, industrial batteries (stationary storage in private and domestic environments, rail, waterborne and aviation transport or off-road machinery). Furthermore, the regulation specifies how the suppliers of battery cells and modules should provide the necessary information and documentation to comply with these requirements.

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The regulation integrates technical and sustainability parameters to guarantee the high quality of products developed in the European Union. A key component of this framework is the introduction of the battery passport, which represents a significant milestone in environmental policy. It functions as a standardised documentation system that provides essential information about batteries, including their composition, origin, history of use and disposal or recycling options at the end of their useful life. Its main aim is to improve the management and tracking of batteries throughout their life cycle. In this way, it aims to increase transparency along the supply and value chains for all stakeholders, improving the exchange of information, enabling tracking and tracing of batteries and providing information on the carbon intensity of their manufacturing processes, as well as the origin of the materials used and recycled.

The Batteries Regulation is also the first legislative piece that imposes a legal requirement for indicating the Product Environmental Footprint (PEF) by providing carbon footprint declaration, which will be linked to the battery passport. These advancements should be acknowledged as a major stride towards intelligent and sustainable product development.

2.2 Expanding Battery Passport to all battery types

According to the Battery Regulation, as of 2027, each Light Means of Transport batteries (LMT), industrial (with a capacity exceeding 2 kWh) and electric vehicle (EV) batteries placed on the EU market must be accompanied by a battery passport. It is important to note, however, that the current focus of the battery passport development primarily centres around well-established battery technologies such as lithium, lead-acid, and nickel batteries, which are all accounting for conventional and cell-based battery technologies.

A product environmental passport enables the collection and seamless integration of data throughout the entire life cycle of a product, from the material sourcing to potential second-life or recycling processes. This data can be associated with the product at any given time, facilitating the tracking of materials and the generation of comprehensive data pertaining to the product itself. Consequently, a large amount of valuable information becomes interconnected, allowing correlation with environmental databases, life cycle inventories of products and processes, and emission factors.

At the current stage, the requirements of the battery passport include only sustainability aspects, such as general battery and manufacturer data, adherence to regulations and certifications, carbon footprint, supply chain due diligence, battery materials and composition, circularity and resource efficiency, as well as performance and durability metrics. The inclusion in the battery passport of additional environmental metrics, like global warming potential, facilitates both macro-level evaluations of the product impacts and micro-level classifications of products based on their environmental attributes. Subsequently, this information can be utilised to influence consumers' purchasing decisions, which has a significant importance in the commercialisation of batteries.

Hence, establishing a level playing field becomes imperative to ensure a fair comparison between the various battery solutions. However, achieving this balance is not always a straightforward task. Two prominent examples may be given. One is the evaluation of the global warming potential associated with the carbon components in battery electrodes. In the case of flow batteries, for instance, battery electrodes undergo a graphitisation process that demands substantial energy input, thereby increasing

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their carbon emissions. On the other hand, in lithium batteries, carbon materials often come from valuable natural graphite, which may have a lower embodied carbon, but at the same time contributes to the depletion of limited and valuable reserves of natural graphite. Another example of the notable distinction between flow batteries and cell-based systems, such as lithium-ion batteries, is their system layout. This disparity is particularly evident in second-life applications, where flow batteries differ significantly from cell-based systems. In a flow battery setup, the number of peripheral components holds greater significance. It is crucial that the origin of these components, such as pumps and pipes, are considered in the setup and that they can be traced after reuse. Consequently, there is a need for frameworks that not only acknowledge the variations among batteries, but also offer reliable guidance on establishing a data collection and follow-up framework to achieve comparable results. This is also applied to other end-of-life routes, such as recycling and the reuse of components like the electrolyte. Beyond end-of-life, there are still data gaps and uncertainties in the foreground and background processes. Databases of raw materials, energy required for processes and other necessary materials are often old or incomplete, especially for alternative battery technologies, where there are fewer incentives to update them.

Future developments in terms of sustainability for the new battery systems will be possible by taking advantages from the very good foundation, which has been already paved by the work for conventional batteries. For instance, in the case of traction batteries, there is a well-established framework with the PEF Category Rules (PEFCR). This PEFCR and its methodology have been used in the past to standardise environmental assessment of cell-based batteries in general. Nevertheless, adaptions need to be done for other battery types.

The definition of the ‘functional unit’ is especially crucial for the sustainability evaluation, as the sizing is usually driven by the application of storage (*Figure 1*). The production system and the functional unit definition sketched in figure 1 will become crucial for the generation of digital twins. The integration of life cycle assessment data into digital twin models is one of the major innovations of this regulation and could play an important role in environmental product passports in other sectors too. For this reason, the outcome of the framework for the sustainability assessment should be ideally developed in collaboration with groups working on this kind of digital tools. However, since applications for stationary battery storage are more diverse and complex than for traction batteries, the integration of LCA data into the digital twins also presents the biggest challenge in this task. Applied research will play a major role in defining the data frameworks for the assessment of different types of batteries. However, only through a broader discussion among all technologies the successful implementation of the battery’s regulation can be ensured. More details on this important aspect of the battery passport are discussed in detail in the *position paper of the Task Force Digitalisation*.

Some important research needs could be formulated to boost the expansion of the digital passport to other technologies:

- Creating a comprehensive framework for the environmental assessment of alternative battery technologies, like flow batteries or high-temperature batteries in relation to their application. Ideally the framework should be linked to open Ontologies like e.g. Open Energy Ontology.
- Creating a comprehensive framework for the environmental assessment of second life of alternative battery technologies.

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- Implementation of application and material specific relevant environmental impact categories (e.g., land-use, water consumption, embodied carbon, resource depletion, human toxicity, ecotoxicity, waste generation).

- Creating new data collections on battery raw materials (e.g., vanadium, phosphate) in the value chain of alternative battery types. It is an imperative, that these data should be collected in Open Source databases for environmental data, which allows the collection of reliable and traceable data, which can be used by the JRC.

- New digital twin models of alternative battery technologies to model especially the use-phase of batteries. It should be actively encouraged that frameworks developed for LCA of new battery types should be linked with projects working on digital twins.

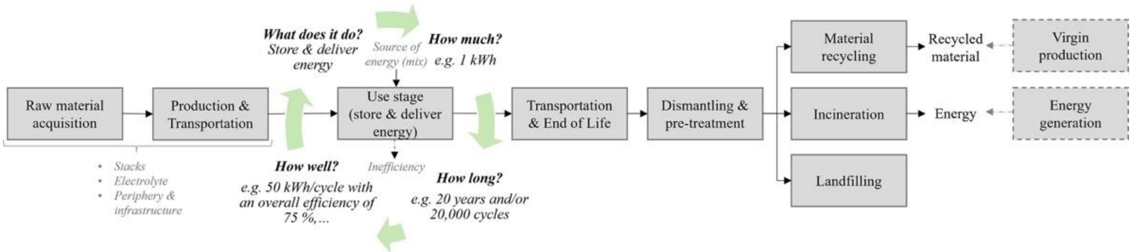

Figure 1: Suggested product system and functional unit definition for LCA of Flow Batteries. Taken from Dieterle M. et al., Life Cycle Assessment (LCA) for flow batteries: A review of methodological decisions. *Sustainable Energy Technologies and Assessments,* **53**, 102457 (2022) /doi.org/10.1016/j.seta.2022.102457. License: CC BY NC ND

All these research needs have a strong link to the Task Force Digitalisation, with whom a stronger interaction is also incentivising.

2.3 Net-Zero Industry Act (NZIA) and Critical Raw Materials Act (CRMA)

In February 2023, the European Commission unveiled the Green Deal Industrial Plan, with the goal of enhancing Europe's competitiveness in the net-zero industry and accelerating the path to climate neutrality. As previously noted, this plan introduced three initiatives, two of which—NZIA and CRMA—are poised to directly influence battery sustainability, alongside the reform of electricity market design.

Through the NZIA, the EU aims to put in place a package of measures and incentives that will make new projects and initiatives more attractive to investors. The Act was designed with a specific focus on the concrete list of net-zero technologies crucial for the green transition, including batteries and energy storage, all of which stand to benefit from the new incentives. Among its many provisions, NZIA aims to reduce administrative burdens for developing net-zero manufacturing projects, simplify permit-granting procedures, establish regulatory sandboxes, and enhance skills and education by establishing the Net-Zero Industry Academies.

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However, the Commission is aware that a clean-tech race is in full swing and none of this will be enough if the strategic dependencies are not addressed. In this sense, one of the key aspects to ensure the EU's independent and competitive position is to guarantee the supply of key critical materials for the continent's production of new green technologies, something that Europe seeks to strengthen through the CRMA.

The goals of the CRMA are mainly: i) to strengthen the different stages of the European value chain of critical raw materials, ii) to improve the EU's ability to monitor and mitigate current and future risks of supply disruption, and iii) to guarantee the free circulation of critical raw materials within the single market. This is to be achieved while ensuring a high level of environmental protection by the improvement of both circularity and sustainability in the supply chain.

The CRMA encompasses a total of 34 critical raw materials that are of great importance to the overall economy of the European Union and for which there is a high risk of supply disruption. Among these, 17 critical raw materials are additionally classified as strategic due to their use in technologies vital for the green and digital transitions, as well as for defence or space applications. The list of critical raw materials is subject to a regular review and update, which are carried out through an assessment based on production, proven deposits within the boundaries of the EU, worldwide distribution of producers, trade, applications, recycling and substitution data, including those that meet or exceed the thresholds for both economic importance and supply risk, without ranking the relevant raw materials in terms of criticality. This list is therefore continuously updated and varies according to the needs of the Union in each review period, following the evolution of technology and consumption patterns.

2.4 Safe and Sustainable by Design Framework (SSbD)

The European Commission initiative for *Safe and Sustainable by Design* (SSbD), announced in December 2022, sets a framework for assessing safety and sustainability of chemicals and materials. The SSbD framework is a voluntary approach and consists of two phases: 1) Design (or re-design) phase, where guiding design principles are proposed to support the development of safe and sustainable chemicals and materials, and 2) Safety and Sustainability assessment phase, where the safety and sustainability of the chemical(s) or material(s) in question are assessed[11]. The SSbD framework encourages innovation to replace hazardous substances in products and processes. Its objectives include developing new chemicals and materials, optimising and redesigning/retrofitting production processes to improve their safety and sustainability, and replacing hazardous substances currently on the market with safer and/or more sustainable options.

The SSbD framework is an essential approach to better integrate safety and sustainability into performance-driven battery chemicals, materials and even cell level design processes. More specifically, both safety and sustainability aspects are considered early in the development process as integral design requirements, alongside performance and functionality. For example, materials, as well as alternative substitution options for toxic or potentially hazardous substances - including those classified as substances of very high concern and/or strategic raw materials (such as battery grade materials) - can be taken into consideration in early development phase.

Guiding design principles and/or frameworks, such as the Green Chemistry Principles[12], or other holistic criteria, should be used to assist in the battery development process. This will also enhance its economic sustainability, as potentially necessary substitutions can be made early, at the design phase of a battery development. This can entail to lower costs compared to making such changes at a later stage, while simultaneously improving safety and overall security of supply of needed materials. The various options in terms of materials and processes should be assessed for their safety and contribution for sustainability. A life cycle thinking perspective should be followed in both aspects, taking into account the battery value chain, as for example life cycle assessment (LCA) for the evaluation of the environmental impacts. Based on the results of that evaluation, measures to improve the safety and sustainability performance of products and processes can be proposed and implemented. This is an iterative process with the goal of progressively improving the safety and sustainability of products and processes, considering the evolution of technology and the needs of consumers.

2.5 Other applicable regulations

Related with the battery supply chain, particularly the supply of raw materials, the EU Minerals Conflict (Regulation (EU) 2017/821) is relevant from a sustainability perspective. The main aim of this regulation is to control the trade of metals and/or minerals that can be potentially used in the weapons manufacturing to fuel armed conflicts, some of which can be also used as raw materials in batteries. The regulation targets EU-based importers of those materials, requiring them to conduct due diligence on their supply chains, thus encouraging responsible sourcing and promoting social sustainability in the process by supporting local communities. The EU regulation is aligned with the OECD Due Diligence Guidance for Responsible Mineral Supply Chains, aiming to promote the sustainability of minerals and metals supply chains. The reason for such alignment is that the future implementation of battery digital passport[13] will require the suppliers to give the costumers evidence that their products follow the applicable rules, thus implying that audit and certify their supply chains.

Regarding environmental labelling, besides the labelling currently used on batteries for safety and recycling purposes, the EU is planning to implement a specific regulation of AG-Scale Energy Label[14] for portable batteries (e.g., those ones used in mobile phones). In practice, it will be similar to the existing AG-Scale Energy Labels that exist for other consumer equipment, in particular domestic appliances. The main goal is to assist consumers in their decision-making about the energy efficiency of the batteries they purchase. The regulation is currently under discussion and the nature of the label and the information it will contain are still under consultation[15].

Other relevant EU regulations are the EU Eco-Design Regulation and the recently agreed Eco-Design for Sustainable Products Regulation. At moment, only the EU Eco-Design Regulation considers batteries through the following key aspects [10]:

- Minimum performance requirements in terms of durability, capacity, charging cycles, among other characteristics.
- Specific environmental labels with the inclusion of parameters such as the carbon footprint. The label will also carry information about performances and a QR code linking directly the Digital Battery Passport.

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- Definition of goals for battery collection targets and set mandatory minimum levels of recycled materials used as raw materials.

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3 ECONOMIC SUSTAINABILITY

Given that economic considerations are the primary driver of virtually all industrial activities, achieving a sustainable battery value chain necessitates careful consideration of the economic framework. Economic sustainability, in this context, pertains to the European battery sector's ability to deliver the necessary technologies and storage capacities within the tight timelines outlined by the Green Deal, thus facilitating the successful transition toward a net-zero economy by 2050. This encompasses factors such as storage costs and affordability, resource availability, workforce skills, diversification of raw material supply, independence from unreliable suppliers, mitigation of supply chain disruptions, and ultimately the establishment of a circular value chain requiring minimal inputs, thereby ensuring inherent robustness.

3.1 Raw materials supply risks & geopolitical considerations

New green technologies overall, and the battery value chain specifically, are geopolitically sensitive, given that a significant portion of the essential raw materials originates from sources outside the EU. The majority of the production of critical battery raw materials is currently mainly outside the EU. Today, only small shares of the total production are EU-based, including Lithium (<1%), Cobalt (<2%) and graphite (<1%). Lithium, nickel and manganese mainly come from South America and Asia, and the largest share of cobalt production originates from the Democratic Republic of Congo[16].

The dependency on individual countries outside the EU for battery raw materials makes the European battery industry and its supply chains vulnerable to geopolitical sensitivities. Furthermore, the growth of the battery demand and the need to secure the supply of raw materials for batteries is leading to international competition that may well affect the geopolitical balance and cause political tensions in exporting countries. The EU therefore needs to act swiftly to ensure that it has access on the global market and can develop additional sources (primary and secondary) for important raw materials. Non-European countries need to have commercial agreements to ensure their supply of the raw materials needed for battery production. Europe also needs to ensure its supply of these important raw materials and develop alternative technologies not relying on these scarce raw materials or technologies.

The same criticalities are observed in the value chain for supplying battery equipment, such as components and machinery for battery production; domains in which the innovation in Europe is high but technical readiness levels remain low in combination with a lower competitiveness from an economic standpoint. As a result, currently the Asian Countries have the largest supplying offer (both for materials and equipment) that is also more attractive economically. In addition, a large share of the battery applications in the European market today depend heavily on battery cell imports from countries outside the EU.

EU research and innovation activities could be the vehicle to boost finding new sources of primary (including mining and refining capacities) and secondary raw materials. This enables the examination of different battery chemistries and alternative materials to decrease the high dependency on importing raw materials and components outside the EU as well as the strengthening of the European

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suppliers and producers to develop mature technologies and skills required to support the battery value chain abilities on the European market.

In the short term (before 2025), the EU ideally needs to put in place mechanisms to secure recurrent access to enough critical raw or refined materials, components and equipment for battery production in Europe at competitive market conditions. The key criteria for the selection of these materials, components and equipment should be traceability (including social aspects), carbon footprint, and sustainable sourcing via short and reliable supply chains (through preferred economical accords). Supporting new business initiatives (production, recycling and others) on current battery technologies (including Li-ion) in the EU is critical to ensure the growth of an economy and trained workforce around batteries.

In the medium/longer term (from 2025 onwards), the EU should focus on supporting the advancement of economically viable technologies, both existing and new, at higher TRLs, while ensuring minimal environmental and social impact. For this to materialise, new businesses should develop in the following fields: new processes, machinery, factory to synthesize, assemble and manufacture current and next generation materials, components, cells and batteries based on fewer scarce elements while targeting high yield, low scrap percentage, less or combined processing steps, low energy consumption and/or combination at plant level with renewable energy (solar, geothermal, wind, and others), low/no solvent processing, water and energy management system, low CO_2 footprint.

3.2 Sustainability of the production outside EU

The premise on which the development of e-mobility rests is that an increased use of Electric Vehicles (EVs) will lower the carbon footprint of transportation. This is recognised by citizens as long as ICE powered cars are in the process of being substituted. Once a sizeable portion of vehicle fleet is electrified, the onus will be on reducing further the carbon footprint of the battery systems. The manufacture of these high value component requires the coordination of a supply chain which starts in mineral-rich countries and leads towards the assembly of battery modules into a final battery at the site of an automobile OEM. The ongoing worldwide effort to decarbonise GDP requires that all manufacturing steps be assessed for their contribution to Global Warming Potential (GWP) emissions. This has been recognised by the European Commission and it is expected that the EU regulatory framework will soon be pushing towards reporting and reducing the carbon footprint of e-mobility batteries.

Creating the scientific and technical foundations for the manufacture of low CO_2 footprint batteries in the EU is therefore a strategic differentiating feature.

3.2.1 New business models enhancing sustainability and competitiveness

Four possible mechanisms would enable established industry and new players to carry out competitive investments with high sustainability standards:

- Development of competitive sustainable technologies for the entire battery value chain.

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- Implementation of the existing eco-label for sustainable battery and battery related products, by including traceability at environmental and socio-economical levels; this could lead to a higher level of responsibility and willingness to pay (customer demand).
- Focused funding policies promoted at both EU and member state levels and/or taxes to achieve the standards for more sustainable, circular and safer batteries.

In addition, adapting new sustainable business models to technology and products is necessary in order to be commercially successful[17]. In sustainable business models (SBM), the elements of value proposition, value creation and delivery and value capture are expanded to include environmental friendliness and social aspects[18]. This will give companies the opportunity to create additional incentives for customers.

The current EU eco-label promotes Europe's transition to a circular economy but focuses mostly on environmental aspects (e.g. less waste, CO_2, energy, raw materials, longer lifetime and easy to repair or recycle). Criteria on socio-economical aspects should be integrated to reflect the broader definition of sustainability.

Obviously, a delicate balance must be found between increasing regulation and/or taxes and keep the economic viability of the battery materials, processes, products and derivatives produced and/or used in Europe.

3.2.2 R&D and low-TRL development

Development of competitive sustainable technologies is the most time-consuming and investment-intensive route. It requires fundamental as well as application-driven basic research. However, favourable policy, targeted regulation, and communication to customers tend to speed up the development. This means also that the research must have an accelerated pace to enable the targeted regulation to be meaningful. In practice this means a better integration of novel tools provided by the new era of digitalisation to improve experimental understanding and advancement in research fields impacting sustainability: green chemistry routes for sustainable synthesis, substitution of toxic material and solvents in electrodes and electrolytes, and lifetime improving studies to enable a safe and long-term use of a battery. In this context, technical aspects such as recycling and raw material efficiency present necessary sustainability advantages. Total cost of ownership can be lowered if the right R&I actions are stimulated to increase the battery reliability [19].

A special attention must be paid to support the creation of new businesses and companies developing competitive sustainable technologies in European R&D centres or research institutes that have not yet been found attractive by the established European industry because of the low TRL (1-2). Ideally, it's important to avoid that those competitive sustainable technologies developed in Europe would reinforce the non-European industry even further by a lack of an internal funding mechanism to bridge the gap from TRL 2 to 6.

3.2.3 Traceability and influencing customer demand

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For manufacturers, responsible raw material sourcing is not only about building consumer trust and protecting brand and reputation, but more fundamentally about securing access to the raw materials required to deliver on their electrification strategies. Moreover, consumers are increasingly aware that their choices have environmental and societal impact. As more and more companies strive to address and minimise such impacts, responsible sourcing has evolved as an important driver generating new business opportunities in tandem to sustainability enhancements.

Transparency and traceability standards will raise interest in customers valuing such battery products. They are possibly willing to pay higher price for higher quality products. This trend has already taken place in the food and textile industries. It is only matter of time when this will become more apparent also in the automotive and energy storage industries.

As further described in the *Position Paper Digitalisation*[20], a traceability system and its link to the DPP will increase the value of batteries and battery materials in their first and second life. This will give room for new business cases and encourage producers to use solutions reducing the societal and environmental footprint of batteries. This information can be used in both B2B and B2C marketing enabling choices based on both quantified and validated environmental and social performance. This requires, amongst others, setting ethical, social and environmental indicators to be measured as well as standards for chain of custody data and active engagement of value chain key players and stakeholders.

3.3 Recycling

Battery recycling is still relatively limited today[21]. Indeed, the availability of batteries to be recycled depends mainly on the available volumes (tonnes) of batteries placed on the market and the moment in which they reach their end-of-life; which is postponed as the battery lifetime enhances thanks to increasingly efficient performances. As such it is important to realise that batteries equipping vehicles today would not become available for recycling before the next 10-15 years[22].

From a circular economy perspective, when it comes to Lithium-ion batteries, there is a need to enhance the design and manufacture from recycled sources. To overcome the current symbolic low recovery rates of some critical materials, such as lithium and graphite, a comprehensive ex-ante life cycle assessment and the life cycle material modelling envisioning also new applications for the recycled batteries material are essential prior to any product design.

Already in the design phase of new batteries, aspects of recycling (on material, cell and battery level) and sustainability should be included. That means methods like design for recycling or design for sustainability should be used at an early stage and be further developed (e.g., the SSbD framework). The expected result of this approach will enhance the valorisation of “waste” material fractions also in case of in closed loop applications.

Furthermore, user-centred analysis involving players in the upstream (waste treatment providers) but also in the downstream value chain (consumers) of the products based on recycled materials need to be anticipated at an early stage of the battery development. Such analysis will ultimately avoid the high economic losses and the prestige burdens due to frequent failures caused by consumer/user rejection upon implementation of “recycled-based” products in the market.

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In the case of battery coming at the end of their life (typically when SOC in Battery Electric Vehicle is below 80% of the initial performance), it is important in the first instance to consider and assess the possibility of re-using (in the same application) and/or re-purposing of battery cells (for another application). Whenever batteries become waste (for example, where further reuse or repurposing is not feasible), they should be recycled (see *Figure 2*). New business models might emerge from re-furbishing and/or re-using battery cells for second use, while the right balance between competitiveness and sustainability is yet to be found and therefore further research and development is needed in this domain.

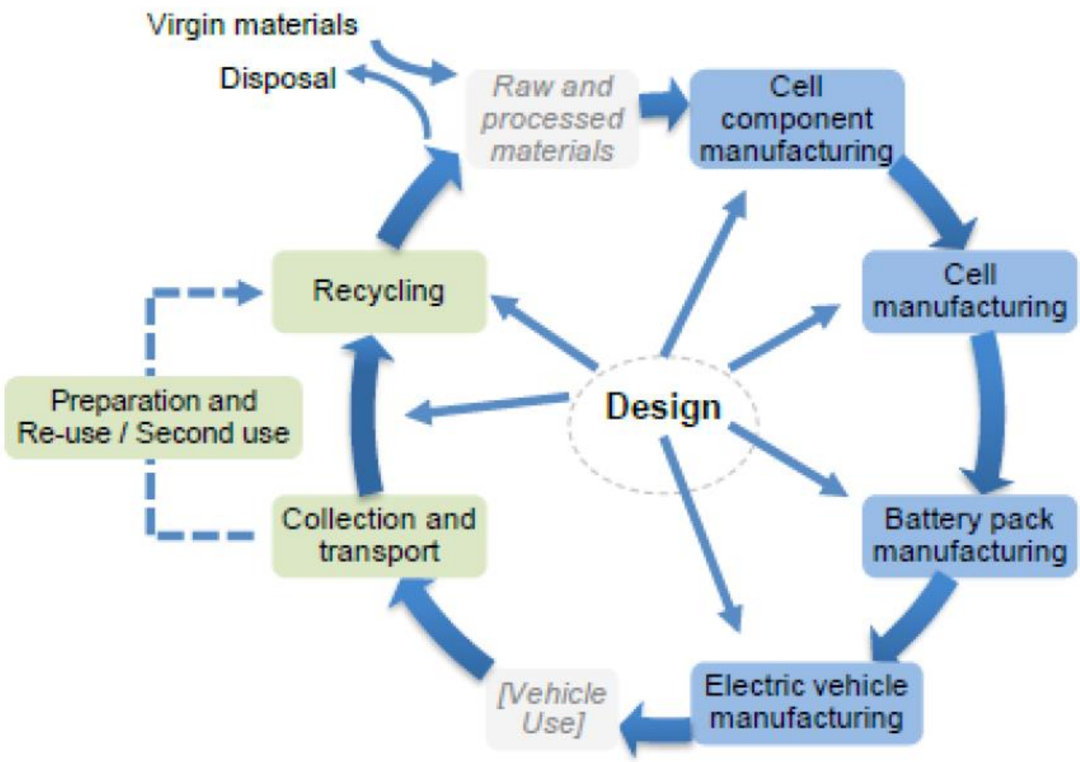

Figure 2: Circular view of the EV battery value chain for Europe. Taken from: Hill, N., Clarke, D., Blair, L. and Menadue, H., Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-10938-9, doi:10.2760/608912, JRC117790.

An in-depth cost analysis as well as an updated LCA inclusive of such options (e.g., refurbishing, reusing or recycling) have to be developed. Note that the sorting and selection of cells to be re-used or refurbished should be cost-efficient compared to new cell cost (decreasing every year) or recycling costs, and automatization assisted by in situ cell sensors monitoring accurately the state-of-health (SoH) of battery cell might help to minimise the cost of this sorting step[12]. Also, an implemented labelling of cells (including for example information on cell chemistry and battery components) would allow a more efficient recycling and thus reducing the overall costs. Last but not least, the safety of such cells should be ensured over both its first and second life.

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Batteries with higher specific energy density will be expected soon to fit the increasing demand for wider vehicle range. It is therefore expected that designs will continue to change in the way of compaction, and the cell chemistry at play will further evolve. In this context, to ensure a solid future of the battery recycling industry, it is highly desirable that their recycled output be able to address a wide range of industries to limit the risks of a loss of downstream markets (which will happen to Pb when it is finally substituted by Li-ion). The need for recyclers to connect their output to the main streams of base metal supplies is the only successful hedging strategy.

3.4 Economic aspects of Second Life Batteries

The market for electric vehicles is growing rapidly representing a total of 14% of all new cars sold in 2022, market share, which is expected to increase exponentially the following years considering existing policies and companies' objectives[12]. When EV batteries' capacity is reduced to around 70–80% of their initial capacity, these batteries slowly become unsuitable for automotive use due to reduced available power. These batteries could be re-purposed in other applications where they will still perform adequately, such as energy storage applications. They are called second life batteries (SLB). This new, second application increases the lifetime of the battery, reducing the need for new batteries and contributing to targets set by the EU regulatory framework for batteries[6]. It is also in line with the European circular economy action plan and the European Green Deal.

Using SLB could create new financial opportunities for different actors in the batteries' ecosystem, such as EVs owners, battery re-purposing companies, SLB users and battery recyclers. EV owners could benefit by obtaining the value recovery of their discarded batteries and a new industry could be created for battery re-purposing aiming to assess, rearrange and repackaging discarded batteries. Moreover, SLB users could buy ESS at lower prices when these include SLB, while battery recyclers could benefit from extracting valuable battery materials from the unsuitable for second life batteries.

However, it is still an uncertain business and some issues related to SLB such as suitable price for SLB, costs of re- purposing and recycling process or the economic viability of using SLB instead of new LiBs need to be addressed.

3.5 Improving technical performance and costs decrease

The already mature lithium-ion batteries can still be improved to increase performances when it comes to both specific energy (amount of stored energy in the battery) and power (level of energy the battery can deliver). Even the lifetime can still be improved to a higher number of cycles that will keep the price low. The expectation is that solid-state batteries with metallic lithium will more than double today's battery capacity when the problem of dendrite formation for lithium and long-term cycling is solved. An overview of the expected new battery chemistries is shown in *Figure 3*. Some of the new concepts have a very high gravimetric capacity but may be less valuable in applications where volumetric capacity is more important (e.g. in private transport applications).

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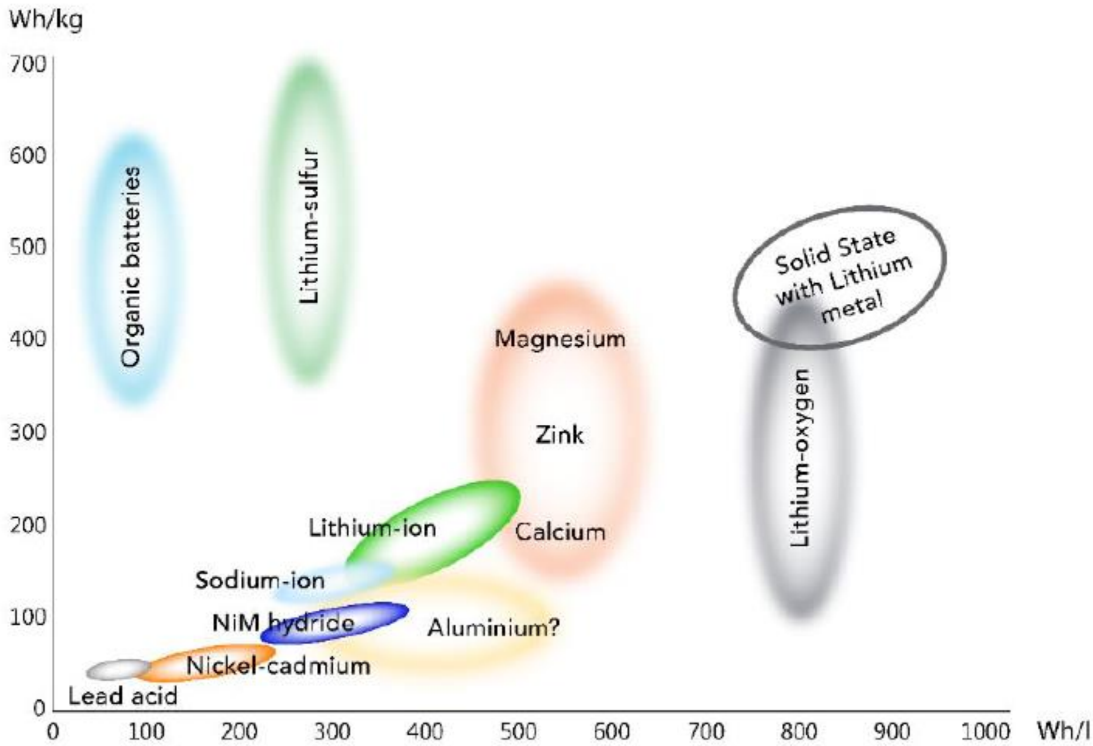

Figure 3: Overview of expected new battery chemistries. Taken from Battery 2030+ Roadmap (www.battery2030+.eu)

Technical performance of the production processes as well as the performance of the products can be enhanced by increasing the information tagged with the products and their intermediates. With the mechanisms beyond state of the art, this target is not opposite to security or confidentiality. Increased transparency within and between organisations increases process efficiency. For example, battery chemical refining, battery assembly, second use, refurbishment and recycling of the batteries would be supported by valuable information on the batteries and material chemistry that could be utilised in, for example, making better decisions/choices and processes more efficient and safer.

3.6 Regulatory aspects related to R&D projects

One key aspect of the regulatory burden linked to R&D&I activities are the burdens and procedures when entering cooperative and EU-funded R&D activities. Criteria such as data sharing, openness of data and transparency when entering research projects could potentially raise the bar for needed R&D&I. Battery production and applications include many aspects of immaterial property rights, such as the chemical development, cell design, BMS programming and stored data on battery usage. As information is a key factor in battery development, EU criteria for data and information transparency, when entering public funded projects, could potentially hamper battery R&D activities in the EU, lowering battery producers’ willingness to receive public funding for such activities.

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3.7 Life cycle Costing

LCC is an economic assessment method that considers all the costs associated with a product or system throughout its entire life cycle. In the literature it is possible to find other names for LCC, such as whole-life costing, or total cost of ownership[15,16]. The methodology adopts an life cycle thinking perspective to analyse the economic performance, similar to LCA but it evaluates economic indicators[23].The life cycle typically includes stages such as extraction and production of the materials and generation of energy required to make the battery, production, operation, maintenance, and end of life, that involve recycling, second use, or final disposal of those materials that cannot be recovered. The goal of an LCC study is to provide a comprehensive view of costs and economic performance of a battery, or of a process system in which the battery is an important part, in a systematic way, rather than just focusing on initial purchase or production costs[24].

The costs taken into account in LCC include not only the direct costs (like manufacturing and purchase costs) but also operational costs such as operating and maintenance, and disposal costs of the batteries. Even though the costs of externalities are not usually considered, recently they are starting to be accounted for. They correspond to the costs associated with the emissions, such as carbon emissions, and the environmental impacts of the various steps of the battery life cycle. In practice, they represent the monetisation of the environmental impacts. These costs can be relevant from a life cycle perspective, for example the impacts of mining can be quite significative from an environmental and social perspective. Even though properly considering the externalities is essential to ensure a fair market comparison of different battery technologies, this is an area where much R&D work still needs to be done. Currently there is lack of data and cost factors to monetise environmental impacts, that depend on many aspects such as the emissions and/or environmental impacts being considered in the LCA study, and local and regional constraints.

3.7.1 LCC Indicators

- An LCC main results are a set of economic indicators, or sometimes just one indicator. Their calculation normally takes into account the time values of money via the utilisation of a discount rate, that depends on the local conditions in which the battery or battery-based system will operate. Hence, the calculated indicators are said to be levelized. Two of the most important indicators usually considered are the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), that correspond to:
- *CAPEX:* Initial investment in equipment and in setting up the battery for operation, as for example protection infrastructure or connection costs to the grid, either taxes or in connection equipment. Depending on the capital initially, large values of CAPEX can represent a barrier for the installation of battery systems.
- *OPEX*: Capital required for operation of the battery system during the battery expected life. It corresponds to costs of maintenance, repair, parts replacement, space rent, grid connection and other activity taxes, among others.

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- From an economic sustainability performance both CAPEX and OPEX should be kept as low as possible. A possible way of reducing CAPEX is significance as a hurdle to the utilization of batteries is a renting business model, in which the investment is spread in time, avoiding the need to make an initial large investment.

From a life cycle thinking perspective, the usage of CAPEX and OPEX is not sufficient, because the costs after the use-phase of the product are not considered. A better cost metric, which essentially captures the cost of storing energy, is the levelized cost of storage (LCOS). LCOS can be described as the sum of the discounted total lifetime investment and operating costs of an energy storage system (ESS) technology (similar to a sum of CAPEX and OPEX) divided by the discounted total electricity discharged from the ESS. The potential cost, or revenues for second use, recycling and disposal can be addressed as costs (revenues have a negative sign) and added to the ratio numerator, thus giving a more complete account of system economic performance. From a profitability point of view, LCOS allows the comparison between different energy storage technologies on a cost-effective basis, helping to understand which option offers the most economical solution for storing and releasing energy. Even though LCOS should be used in conjunction with other indicators and taking into account other aspects, as for example the technical viability, it is nevertheless an important metric to understand the economic viability of energy storage technologies and promoting their integration into a sustainable energy future.

3.8 Competitive battery industry: Jobs, reskilling and training

Jobs, reskilling and training are pre-requisites for a fast transformation to a fossil-free society, (this subject is extensively discussed in the *Position Paper Education & Skills*) [25]. The multidimensional concepts constituting sustainability, including knowledge about raw material and production of battery materials for mining are the basis for the design of new training schemes for education at academia as well as re- and up-skilling the workforce to meet the new demands. The EU expects an increase in battery cell manufacturing capability in Europe up to 25% by 2028 [26]. This expectation needs to be met with an increasing workforce handling production technology, but also in all parts of the battery value-chain: materials, recycling, applications, and others. From a sustainability perspective, this includes understanding how processes at all levels can be made to decrease CO_2 emissions. For some of the actors, it means also knowledge about the legislation or how toxic batteries or production of batteries can be, if not handled correctly.

Europe has a competent class of engineers working in the transportation sector. Most of these are trained for combustion engine drivelines. Re- and up-skilling this group will be vital to achieve the best benefits of the new battery systems for different applications. Sustainability is related to the life expectancies of batteries, and proper knowledge of how to improve drivelines powered by batteries is a necessary new skill but also how to select the most sustainable product to fit to the application purpose.

To increase the speed for the transition to meet the targets set out in The Green Deal means also to influence the attitude of prosumers to accept the new technologies. It is then important that the information provided for the general public is based on facts and honesty, reflecting the impact of the technology to the environment.

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In summary, education for sustainability in this sector means development of new curricula for:

- Engineers that are reskilled to handle electrical drivelines
- Materials and battery cell producers understanding the sustainability requirements for batteries to be able to develop better and cheaper methods
- Legal representatives who understand the basics of batteries and sustainability
- Environmentalists to understand when a battery is toxic or not and to put the battery's qualities in the right perspective
- Economists to build new business models, including the role of sustainability into their perspectives
- The general public to learn enough to take motivated decision as consumers of the different applications.

A general knowledge and appreciation of life cycle assessment will be important for all above-mentioned groups.

3.9 An industrial and global marketing perspective

Sustainable battery technologies will need successful commercialisation strategies. This would require early engagement with leading EU battery user organisations. Such actors are not just market leaders, but they are also known for their ability to adopt innovation. Engaging with corporate stakeholders will provide insights on how battery technology develops. For this to happen the continuous engagement of the stakeholders for oversight in the transition process is suggested. Industry partners can also help to identify the procurement bottleneck for green batteries, e.g. change in relevant quality standards and public procurement norms in not just EU but other major economies like China and India.

Ultimately, the success of a new EU battery policy will depend on global adoption of such standards in emerging economies, not forgetting at the same time the working conditions (safety and human rights) in the battery disposal and recycling industry of the global South. The new EU policy should have outreach provisions to educate stakeholders in the global south as well as consider the constraints of the standards adoption in such markets.

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4 SOCIAL SUSTAINABILITY

Social sustainability in the context of batteries encompasses the examination and integration of social considerations throughout the battery life cycle, from sourcing materials to end-of-life disposal. This involves assessing and addressing the societal impacts associated with the production, use, and disposal of batteries, including labour practices, community engagement, and ensuring equitable access to the benefits of energy storage technologies.

The mission of the dedicated Task Force *Social Sciences and Humanities*[27] focuses specifically on societal impacts and human aspects of the battery value chain, with the objective of promoting sustainable practices and equitable access to energy storage technologies. The Task Force and its Position Paper aim to deepen the understanding of the various societal facets associated with batteries in Europe.

4.1 Social Life cycle assessment (S-LCA)

Social life cycle assessment (S-LCA) is considered a comprehensive methodology that aims to assess the positive and negative social impacts of a product or service. The methodology is described within the technical report of JRC [28] and SETAC [29]. Social LCA is becoming more prominent as a means of evaluating social impacts. Efforts are underway to standardise social LCA methodologies globally and establish best practices. The International Standards Organisation (ISO) is in the process of creating an ISO 14075 standard for social lifecycle assessment, aiming to standardise approaches and promote best practices.

Even though there are positive signs towards a worldwide development and adoption of S-LCA, considerable improvement is needed to the different databases that more often lack substantial information. There is a lack of information on social impacts of the sourcing, production and recycling of batteries. The methodology for S-LCA is still developing even though the UNEP/SETAC guidelines on S-LCA have been reviewed through UN pilot studies. The interpretation of the results is difficult, because often the uncertainties are higher than the differences of the compared options.

However, S-LCA offers a complementary approach to considering social impacts of a process alongside the assessment of environmental impacts using traditional LCA and whole-life cycle costing. The S-LCA should reach end customers to encourage choosing sustainable products over others. Proposed eco-labels for batteries should include social traceability criteria based on S-LCA results to enhance material and process transparency. The eco-label framework for batteries[14] can help global customers identify sustainable products with ease and adopt them for their own use and processes.

Regarding stakeholder categories, an organisation's effectiveness in interacting and engaging with its stakeholders significantly influences its social performance. Organisations, whether directly or indirectly, impact the well-being of stakeholders, underscoring the need to proactively manage these social impacts. The stakeholder categories outlined in the S-LCA Guidelines[30], established through discussions among experts, include workers, local communities, value chain actors (such as suppliers), consumers, children, and other societal entities.

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4.2 Due diligence

The European battery industry faces disparities, with production outside Europe receiving substantial support from local governments, placing Europe at a disadvantage. As demand for batteries and raw materials is expected to rise substantially in the near future, European production, particularly in raw and advanced materials, may struggle to meet demand. There's a pressing need to level the playing field for European actors and this can be achieved by benefiting from the consideration of the social aspects of battery production. Imported materials currently overshadow European production, often tied to social issues like child labour and inadequate occupational safety. Implementing a traceability system would empower consumers to make informed choices based on social factors, aiding both consumer selection and regulation. This initiative is anticipated to drive improvements in social conditions throughout the battery value chain, particularly in raw material production.

It would be greatly ironic, if not outright unsustainable, if the growth of this industry was built on below standard, or just average environmental and social practices. Amongst key elements of the growth are the recognition that the battery industry has to ensure, throughout its supply chain, the implementation of due diligence obligations with regard to labour rights and environmental protection.

In order to ensure these values are upheld, the battery industry has to implement the five steps of a due diligence plan:

- Get to know the supply chain and identify the risks
- Encourage transparent public reporting
- Conduct third party evaluation of suppliers, in line with the identified risks
- Implement risk mitigation programs where deviations have been identified
- Deploy a claim gathering mechanism to capture violations
- Implement a follow-up mechanism to assess the deployment of mitigation measures and their effectiveness.

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5 ENVIRONMENTAL SUSTAINABILITY

5.1 Life cycle assessment and carbon footprint

Life Cycle Assessment (LCA) is a methodology used to evaluate the environmental impacts of products and processes. It is standardised by ISO 14040:2006/ 14044:2006[31] and has been widely applied to batteries. Also, RECHARGE – the Advanced Rechargeable & Lithium Batteries Association has developed Product Environmental Footprint Category Rules (PEFCR) for high specific energy rechargeable batteries for mobile applications. The environmental impacts of battery manufacturing are driven by energy production when focusing on GHG emissions and carbon footprint[32]. However, other impacts such as toxicity, air pollution, water footprint and resource depletion show that raw material extraction and processing are key stages. There is a need for development of models and data required to assess these additional impact categories[33].

The sustainability criterion obtained from LCA can be used to compare the environmental performance of different battery products, and to select between alternative process development routes for manufacture of battery components and technologies for recycling of raw materials at the end-of-life. Many existing LCAs are based only on few original primary datasets (e.g. energy and raw material consumption), which significantly increase the uncertainties of the environmental impact results. Thus, there is a need for more and better primary data to support more robust LCA modelling studies. Especially for the whole production process (on industrial scale), the key raw materials used to prepare the battery precursor chemicals for the active cathode materials (e.g., metal sulphates, and others) and anode materials (e.g., graphite) and the different recycling processes. These primary data are often represented using proxies and outdated or incomplete datasets. For the pre-chain of raw materials, there is also a need for regionalised LCA data for mining, such as water footprint and harmonised energy source declarations from exploration to products. Regarding the use phase in different application fields, all relevant performance indicators (e.g., internal resistance, cycle lifetime) need to be taken into consideration, to allow a comprehensive and fair comparison. More reliable LCA data, and disaggregated data on the production and recycling processes could support more comprehensive evaluations of the primary and secondary materials. This implies also for the recycling process and battery type (e.g., NMC111, LFP) the need for specific approaches in the future.

Beyond advancement in the data and models for pure LCA studies, the PEF Category Rules should be extended from the battery product level to also consider primary data for the active electrode materials, and battery components (e.g., cathode and others) as well as secondary data from recycling of battery components at the end-of-life.

5.2 Use of hazardous materials

Looking at the current battery chemistries, the use of toxic, explosive and hazardous materials in manufacturing are being managed and well documented, and a series of countermeasures are taken

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for those materials or systems addressed by risk management measures, while the potential harm caused by the end-product on the environment is typically addressed by risk avoidance measures. At present, toxic and hazardous materials can be found in LIBs, especially in active components like cathode and electrolyte. For the manufacturing of these batteries in the future, efforts need to focus on the: (1) safe management of hazardous materials; (2) substitution of hazardous materials with safer alternatives if feasible; and (3) reduction of hazardous materials where possible. In such cases, the attention points should ensure that technical performance of batteries remain high, while the processes are upgraded to a more environmentally friendly one and still be cost-efficient.

Most hazardous substances are today regulated in the EU REACH regulation[34]. It is worth noting that the battery industry is currently growing, leading to increased use of regulated substances. Safe management of these materials is key. One critical global sustainability issue is the fact that restricted use in the EU might increase production of the material/substances in other parts of the world, where regulations are less comprehensive. Substitution of hazardous substances is therefore a priority to increase sustainability along the entire value chain.

The next generation batteries might bring new risks for the environment and the workers linked to the use of those potentially toxic, explosive or hazardous new materials. Those risks and impacts on environment (during both the elaboration of the materials or battery or potential harm caused by the end-product on the environment) still need to be mapped, assessed and compared (for each new technology using standard protocols to be defined), while countermeasures should be developed. Identifying such environmental aspects at early stage, namely, during the design and production processes is crucial to ensure that future battery technologies are sustainable and economically viable compared to the current commercial batteries.

5.3 Per- and polyfluoroalkyl substances (PFAS)

Per- and polyfluoroalkyl substances (PFAS) represent a vast and varied category of chemical compounds described also in the ECHA database[34]. The Organisation for Economic Cooperation and Development (OECD) defined PFAS as "*fluorinated substances that contain in their structure at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom bonded to it*)", that means any chemicals with at least a perfluorinated methyl group (–CF3) or a perfluorinated methylene (-CF2-) group"[35]. The OECD report acknowledges that the term "PFAS" is broad, general, and nonspecific, which does not inform whether a compound presents risk or not, but only communicates that the compounds under this term share the same structural trait of having a fully fluorinated methyl or methylene carbon moiety. Further, the report highlights that, among the substances defined as PFAS, there are distinct substances with very different properties, namely polymers and non-polymers, solids, liquids and gases. PFAS have recently come under scrutiny due to their persistence and corresponding accumulation in the environment, with some of them accumulating in drinking water, animals and humans, eventually causing toxic effects.

Fluoropolymers fit in the broad definition of PFAS by OECD[15], but they should be considered as separate classes of polymeric PFAS that fulfil all criteria of "Polymers of Low Concern" (PLC)[36]; they have high molecular weight, cannot be absorbed by cells, are not bioavailable and do not show any toxicity. Therefore, Fluoropolymers may be considered as a special class of PFAS substances[37].

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PFAS are used in batteries[38] in two key areas, consisting mainly of polymers of low concern[16], such as PVDF and PTFE. They are commonly used at the electrode level as binders, in solid electrolyte/gel polymer electrolytes and as coatings for the cell separator. PTFE, FEP, FKM, PFA, VDF-HFP are also considered in gaskets, pipes, valves, various sealings, washers. Fluoro-carbonates of esters are also typical additives in liquid electrolytes formulation.

Fluoropolymers have unique properties (e.g., high electrochemical, thermal and chemical stability, good adhesion and dispersion capability, efficient electrical and thermal insulation), which is why they are used in batteries. While PFAS free binder are under investigation and tested on small test cells,[39] these still do not deliver the same performance as the established materials. In some applications non-PFAS alternative materials have proven to be at an acceptable level of performance. For instance, in valves, gaskets or washers in mild temperature ranges, non-PFAS gasket sealing materials like PPS, PBT or PEI provide an adequate sealing performance. However, in high energy density lithium batteries, the required stability for high power and high temperature cells can only be provided by PFAS-based materials such as PTFE, PFA, FEP, VDF-HFP and FKM [40].

Nevertheless, some companies promise to have PFAS "free" Lithium-based battery systems on an industrial level produced and in operation mobile and stationary applications, for example Leclanché [41].

5.3.1 Environmental aspects, End of life and recycling

Based on the importance of a sustainable life cycle, care has to be taken to avoid that dangerous PFAS and other toxic materials contained in current batteries are released to the environment at the end of the life of the battery. At industrial level in Europe, batteries are currently recycled by means of pyrometallurgical and/or hydrometallurgical processes. In the pyrometallurgical process, the batteries are treated at high temperatures, between 1400°C and 1600°C, to extract metal elements such as Nickel, Cobalt, Copper, similar to the ore smelting reduction stage. At these high temperatures, all PFAS used in batteries are fully dissociated into fluorine compounds[42] so that there are no PFAS emissions from the pyrometallurgical process[43]. In the hydrometallurgical process, the metals are recovered through solvent extraction or resin extraction technologies. Fluorinated compounds such as PVDF and PTFE are captured in the waste solvent / resin and other waste fractions. The recovered PFAS are then treated at high temperatures to fully decompose the fluoropolymers.

From a PFAS perspective, hydrometallurgical processes excluding a thermal pre-treatment at high temperature are therefore more critical due to potential PFAS emissions. Hydrometallurgy development is actively proceeding, and further R&D activity would be required to support the optimisation of more sustainable processes with better control of key processing steps in order to avoid hazardous emissions.

Moreover, it is known that a significant share of EoL batteries are not returned for controlled dismantling and scrappage in Europe. How the batteries coming from such informal channels are actually recycled is still unknown; therefore, further awareness is required on the actual fate of EoL batteries, the recycling pathways and the related PFAS flows into the environment.

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In summary, substantial efforts are required to eliminate PFAS from the battery value chain, given that non-hazardous PFAS classes of materials, such as Fluoropolymers, play still an essential role in the present batteries manufacturing and have to be managed in a sustainable manner along the full life cycle. Care has to be taken not to anticipate decisions that might lead to unintended negative effects such as reduced safety and lower lifetime. Two “roadmaps” or approaches are necessary to address the PFAS issue in and adequate manner, which require a tremendous research effort:

- A first approach focuses on the question how to prevent in the near future the emission of hazardous PFAS to the environment due to reuse or recycling of batteries which are already placed on the market. As sustainable end-of-life management and state-of-the-art recycling processes developments are fundamental steps in battery roadmaps, further research activities are necessary to develop more sustainable recycling processes and identify alternatives where technically feasible. Development of improved analytical methods for accurate PFAS determination and quantification is another field that research activities should focus on.
- A second approach focuses on the question how to eliminate or at least reduce the usage of hazardous PFAS for the production of present and future battery chemistry systems, develop alternative materials and assess them under consideration of the whole life cycle of the battery. This requires a significant research effort in the long-term horizon.

Any replacement initiative of PFAS materials should always be accompanied by a full life cycle perspective. The unique properties of fluoropolymers are essential for delivering the high performance of current high-energy LIB and to help deliver strategic EU and UN climate objectives. If the replacement of such materials would come at the expense of important properties such as safety or lifetime, this may cause increased impacts elsewhere and could be counterproductive.

5.4 Resource use across the value chain

Production of batteries and battery applications requires large amounts of resources. Critical inputs across the value chain are raw materials, chemicals, water, electricity and potentially other fuels. The environmental impact of batteries must consider the use of resources throughout the value chain, from the extraction of raw materials and their refining, through the production process, the use phase and, finally, the end-of-life.

R&D&I activities can contribute to resource efficient batteries by promoting and developing new products and processes with resource efficiency KPIs. The resource use can also be estimated by using a thorough LCA analysis. Possible activities are sustainable processing of elements for active battery components, production of materials and electrode components stable in water-based processes, treatment of wastewater, circular material and resource flows in manufacturing processes and replacing and development of new solvents.

The battery value chain consumes energy in mining, refining, production, use and recycling of batteries. As the energy need is especially large in the production process of batteries, R&D&I activities should support, promote and stimulate the use of renewable electricity for production, reducing the need for natural gas and fossil fuels in the production process as well as the other steps of the value

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chain. Sourcing of electricity, to validate emissions related from energy consumptions will be a critical tool to assess the environmental impacts from resource use.

At the same time, battery application often stimulates a more efficient resource and energy use, compared to the alternative technologies they replace. R&D&I activities increase the use of batteries and promote electrification in more sectors and will hence be important tools to increase resource efficiency by, for example, electrifying machinery, powered tools and transport applications.

5.5 Environmental aspects of recycling

Recycling is a relatively labour-intensive activity, as workers are still needed for separating materials from each other before they can be mechanically or chemically treated. A traceability system, including the information of material chemistries and battery life would help in extending batteries' first life to second life and, in the recycling stage, feeding information to the recycler on what kind of processes should be used to maximise the recovery and value of the material. It would also give information on the unrecovered materials and help in finding new innovative solutions for using or recovering those materials.

The early design phase of batteries determines the future recycling options and possibilities. Therefore, the potential recycling should be considered on material, cell and battery level as early as possible. Methods like "Design for Recycling" can be adjusted and applied. A major challenge of the future recycling will be the potential very low material value in battery cells. Thus, present recycling technologies are not sufficient, because they require large amounts of energy and chemicals. Here, physical recycling technologies could be an option to allow potentially a (rather simple) direct recycling of active materials. In any case, the future recycling options depend on the design decisions in low TRLs. Therefore, it is necessary that Post-LIB developers interact with recycling experts as early as possible to ensure a low effort recycling technology in the future, which is important to be competitive with other technologies like H_2, power2X, or flow batteries.

Overall, battery recycling could potentially reduce energy consumption and GHG emissions and result in considerable natural resource saving. Preformed studies show, however, that the benefits of battery recycling are not unequivocal, and the environmental benefits is an area in great need of further analysis. At present, it seems that Li-Ion battery recycling has some disadvantages regarding environmental impacts against the recycling of, for example, redox flow batteries [44]. Some studies show that the largest contributors to the environmental impacts are electricity generation, incineration of plastics and landfilling of residue. In terms of environmental effects, it is suggested that the most beneficial processes are those that utilise low temperatures and can recover plastic. Comparative and ex-ante life cycle assessments need to be performed for the different recycling processes in order to accurately define the associated environmental impacts and act in consequence.

However, it is yet to be determined which recycling processes have the least impact on the environment. There is thus a need to investigate the different processes currently used for recycling batteries, such as hydrometallurgy, pyrometallurgy, combinations and direct recycling. The physical

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recycling processes and a direct recycling of battery materials and cathode components also show future potential.

Research should be conducted to ensure that all recycled substances extracted from batteries are refined to the level that allows them to access the widest stream possible, or to the level that causes the lowest sustainability impact.

5.6 Environmental aspects of Second Life Batteries

Second life batteries are batteries that are re-used (or continued to use) after they have reached their end of life in the application they were originally designed for. This is assumed to provide environmental benefits by extending the lifetime of the batteries for several years according to the waste hierarchy (re-use).

The primary benefit of SLB from an environmental point of view is to avoid the production of new batteries, and hence decrease the impacts related to the first life battery manufacturing [45, 46]. However, the benefits of SLB are not always evident. While using second life batteries would decrease the primary materials demand due to the avoidance (or delay) of the production of new batteries with all the corresponding environmental and social impacts, it will also postpone the availability of batteries available for recycling and hence the recirculation of secondary raw materials. Also, evidence on the remaining performance and lifetime of batteries that have reached their end of life is still scarce, constituting a barrier for second life use. Similarly, evidence is lacking about when EV batteries become EoL batteries, and up to which point they may be re-used in the primary application as replacement parts by vehicle owners that have lower performance requirements.

Research is therefore needed on several key aspects, such as the actual battery degradation mechanisms, EoL trigger criterial, second-hand battery and spare part markets, the remaining performance of EoL batteries when becoming available for potential second-life use, suitable applications and the share of new batteries than can actually be avoided within these applications. Furthermore, lower performance of second life batteries such as increased internal resistance or self-discharge may also be detrimental for the environmental performance, requiring thorough assessments of all the related aspects before drawing premature conclusions.

5.7 Methodological challenges for comprehensive sustainability assessment

Current sustainability assessment methods typically quantify environmental (and sometimes societal) impacts of energy storage but these methods often remain at technology level. They allow to design batteries in the sense of reducing the environmental (and social) impacts related with their production, use and disposal, but do not consider aspects of absolute sustainability, such as planetary boundaries, resource availability or also the contribution to achieving social objectives. Under this currently prevailing technology-centred paradigm, more batteries will better support the energy transition, while evidence shows that there are absolute sustainability limits. Approaches that develop assessments against planetary boundaries have recently emerged, but they are still under

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development. However, a comprehensive sustainability assessment should consider such limits and therefore include also demand-related aspects and consumption-oriented measures for minimising environmental impacts and resource demand. These are related with questions of efficient use of the battery stock, appropriate battery size, mobility behaviour and sufficiency, among others, and therefore have a strong link to the Task Force *Social Science and Humanities* (TF SSH). Such questions need to be investigated further, also incentivising a stronger interaction with this TF and related questions.

A second challenge arises from the multidimensional nature of sustainability assessment. Quantitative methods like Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social-LCA can be used to analyse the potential sustainability impacts of developed batteries over the entire live cycle, each one focusing on one of the sustainability dimensions described previously. However, due to the wealth of different impact categories and their often contradicting, communication to stakeholders and decision making is difficult, Multi Criteria Decision Analysis (MCDA), or other decision-making methodologies, can use the results of the sustainability evaluation methodologies and address the different dimensions of sustainability in an integrated way to analyse and evaluate in a holistic manner the technology in the R&D phase or products, in order to identify the more adequate course of action and define and implement measures to improve their sustainability. With the consideration of economic, ecological and social assessment results of an analysed technological artefact (like batteries), MCDA helps to understand the sustainability implications. The assessments of the sustainability of a technology or option requires the consideration of a wide variety of information types (both quantitative and qualitative), parameters and related uncertainties, which is a challenging task. MCDA is a suitable methodology to combine and condense the different outcomes of the sustainability dimensions (which can be conflicting) towards a certain decision or selection. In addition, MCDA can be used to analyse and determine the preferences of the society or specific stakeholder group regarding the weighting (of the importance) of the different sustainability dimensions.

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Research and Innovation Programme under Grant Agreement N. 101069676

6 CONCLUSIONS

Sustainability requirements are a cross-cutting topic that impacts all the different steps of the battery value-chain, and which has to be considered through the social, economic and, of course, environmental perspective. In order for the battery value chain to fulfil the sustainability requirements needed to set up a strong battery industry in Europe, specific challenges still need to be overcome. R&I is still needed to achieve a future battery system which has a significantly better performance and better environmental footprint than today, including the elimination or reduction of PFAS usage.

Moreover, competitiveness and sustainability, two aspects that can be hard to articulate, need to be thought of in relation with each other, especially in EU regulations and dissemination action that can address this potential conflict. Dissemination actions towards end-customer via the introduction of a new ‘sustainability label’ going much further in scope than the current ‘eco-label’ might help over win the dilemma sustainability versus competitiveness. Sustainability appears as a key factor that industry must take into account in order to ensure the green energy transition, and which needs to be integrated from an early stage in order for the industry to succeed.

Other important R&I activities are needed:

- Develop a common evaluation assessment of the sustainability of batteries, in particular their environmental impacts over the whole life cycle. Possibilities may be the definition of Product Categories Rules, PCR, that define a common set of environmental indicators, considered system boundaries, and impacts evaluation methodology, that should be applicable regardless of the battery chemistry. This way the reporting of the environmental performance of batteries can be made in a uniform way.
- Define standards for the transfer and handling of sustainability data, in particular environmental information. The standards should include information about the data, uncertainty, used background database, year specification and other information. Protocols should be defined to ensure anonymity.
- Propose the development of guidelines or guides of good practices to increase the sustainability of battery production or recycling processes. They may be similar to the existing best available techniques (BATs,) BAT Reference documents[47], but focused on battery production.
- In addition to the technological development of batteries, the reduction of the environmental footprint and social impacts will be one of the core elements of mobility and energy transition. Individual initiatives to make production more environmentally friendly, to reduce the use of raw materials through recycling and to increase the welfare of employees and society must continue to be driven forward. However, this will only be possible if industry and the academic research community and society are prepared to support these projects.

The aim is to investigate which business models can support companies to continue generating profit without neglecting the environment and social responsibility. There are already initial approaches here with sustainable business models and modified value chains[48]. Further research is also needed into the options available to customers to find a balance between protecting the environment, ensuring global social responsibility and the price of purchasing or using products and services.

This project has received funding from the European Union’s Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

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This project has received funding from the European Union’s Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

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Position paper

Social Sciences & Humanities Task Force

April 2024

In cooperation with

BEPA
Batteries European Partnership Association

ACKNOWLEDGEMENT

Batteries Europe Secretariat is an EU-funded project that has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676.

DISCLAIMER

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Acknowledgements: We would like to thank Spyridon Pantelis (EERA) for the overall coordination of the Task Forces, Alessandro Romanello (EIT InnoEnergy) as coordinator of Batteries Europe, and the BEPA Secretariat for their support in the operation of the Task Force. Special thanks to Fatima Ahmed, Adeola Adeoti, Lucia Sardone (CLERENS), and Maria Luisa Fernandez Vanoni (EERA) for editorial support. We would also like to acknowledge the inputs and considerations from the European Commission, the Batteries Europe Secretariat and Batteries Europe Advisory Board.

This project has received funding from the European Union's Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

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Research and Innovation Programme under Grant Agreement N. 101069676

ABBREVIATIONS AND ACRONYMS

Abbreviation	Definition
BE	Batteries Europe
BEPA	The Batteries European Partnership Association
BESS	Battery Energy Storage Systems
EV	Electric vehicles
GDP	Gross domestic product
ILO	International Labour Organization
ISCED	International Standard Classification of Education
LCA	Life cycle assessment
LFP	Lithium iron phosphate
PSILCA	A Product Social Impact Life Cycle Assessment database
R&I	Research and innovation
RRI	Responsible research and innovation
S-LCA	Social life cycle assessment
SDGs	Sustainable Development Goals
SET Plan	Strategic Energy Technology Plan
SETAC	Society of Environmental Toxicology and Chemistry
SRIA	Strategic research and innovation agenda
SSH	Social sciences and humanities
STEM	Science, technology, engineering, mathematics
TF	Task Force
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
WG	Working group

This project has received funding from the European Union's Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

Executive Summary

In response to the need for a comprehensive understanding of the societal implications and human dimensions of battery technologies, the Batteries Europe/BEPA Task Force (TF) on Social Sciences and Humanities (SSH) presents this position paper. In contrast to most of the other TFs, **TF SSH is one of the two recently established cross-cutting TFs and as such, the position paper presents the results of an initial exploration of the role of SSH in battery development and deployment.**

TF SSH mission statement:

- to strengthen the interdisciplinary framework of Batteries Europe through the incorporation of both STEM and SSH disciplines and identify research funding needs;
- to enhance understanding of different societal dimensions related to batteries in Europe;
- to engage in discussions regarding the societal dimensions with key stakeholders within the Batteries Europe platform;
- to raise awareness about the societal implications and human dimensions of battery value chain, aiming to ensure sustainable practices and equitable access to energy storage technologies.

This position paper offers an **analysis of the current state of research within the 'SSH for Batteries' area, highlighting the complex interplay between technology and society.** It explores both technology-focused and human-centric viewpoints, raising critical questions about what characteristics make a battery not only technologically effective but also beneficial for society at large. The paper also emphasises the importance of recognising the needs and contributions of the industry, incorporating practical insights into the broader discussion.

The goal of this document is primarily to **inform the Batteries Europe community and other key players (interested stakeholders) on the need to integrate SSH disciplines and themes into the R&I agendas of battery technologies.** It aims to spotlight SSH research areas in need of Horizon Europe funding, underscoring the value of SSH insights in advancing battery technology development. Furthermore, the paper advocates for the development of an SSH framework specifically designed to address the challenges and prospects battery technologies offer along the entire value chain. It provides SSH research gaps and offers policy recommendations for enhancing SSH analysis of battery supply chains.

By presenting key findings and evidence from existing SSH research on batteries, the paper aims to **bridge the gap between technological advancements and the socio-cultural reality within which these technologies operate**. The outline framework for SSH aims to guide the Batteries Europe community in aligning technological progress with societal well-being. Recognising the synergies and overlaps between TF SSH and other Batteries Europe working groups and cross-cutting task forces, fostering collaboration, mutual understanding, and contributing to identifying new research gaps in the other cross-cutting areas of the battery technologies' research.

The research review reveals that existing SSH studies on batteries are mainly concentrated on economic and business aspects, enriched by insights from sociology and political science. These studies provide on one hand a deep understanding of the risks and opportunities in battery

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development, but on the other hand are missing more interdisciplinary frameworks to guide the process effectively.

An outline SSH framework shows possible ways of the integration of SSH into the battery technology realm. By advocating for a transdisciplinary approach that merges SSH with STEM disciplines, the **TF SSH aims to foster effective research and innovation in batteries, establishing a foundation for structured collaboration between SSH and STEM fields in Europe's battery research and innovation landscape.** To demonstrate the concrete examples of incorporating SSH aspects in batteries technology, the paper presents examples of research projects, published case studies, as well as TF members' personal perspectives.

Case studies in the paper demonstrate how applying the SSH framework can enhance societal relevance in battery and renewable energy initiatives, offering insights from existing research on social risks, public acceptance, and policy drivers to inform future projects. Moreover, the paper identifies **gaps in SSH perspectives**, proposing a set of research questions to address these gaps and enhance SSH contributions to battery research.

Recommendations and broader policy implications for including SSH topics within the Batteries Europe community are presented, addressing potential challenges and obstacles, and policy implications within the context of the European and global clean energy transition.

In conclusion, this position paper invites Batteries Europe community, and other interested stakeholders including policymakers and industry stakeholders **to embrace a "human-centric paradigm", where SSH becomes an integral part of technological and societal progress.** It calls for collaboration and dialogue, and proactive measures, such as including SSH agenda in the innovation funding and implementation mechanisms.

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1. INTRODUCTION

Highlights of this part:

- *Batteries are pivotal in the energy transition, enabling vehicle electrification, renewable integration, and mobile device operation.*
- *Battery demand surges by 30% annually, pressing for environmentally and socially sustainable practices.*
- *Advocates for sustainable battery innovation stress the importance of societal well-being and ecological integrity.*
- *The SSH Task Force advocates for battery development that champions social equity, environmental stewardship, and economic inclusivity.*
- *The document urges embedding SSH insights into battery research and policy frameworks for comprehensive sustainability.*

Batteries represent key enabling technology in the clean energy transition. They enable the electrification of the transport sector, support the shift of the electricity sector towards renewable generation technologies and are required for virtually all handheld and portable devices. In consequence, the global battery sector is predicted to grow at staggering rates of up to 30% annually and even more in short and near-term future[1]. While such rapid deployment of technology is required for achieving decarbonisation goals on time, it also brings along challenges related with environmental and social sustainability. Efforts are required to ensure that such a rapid development follows sustainability criteria, does not cause negative unintended or unforeseen side effects and that it is of overall benefit for society. Part of these aspects are addressed by the TF Sustainability and partially also by other Task Forces (TFs) and Working Groups (WGs), however with focus on technology-centric aspects such as battery design or material choices rather than on society and its needs.

For this purpose, Batteries Europe has established the cross-cutting TF SSH with the aim to explore the role and potential of SSH research related to the European battery value chain. For instance, the expected high growth rates and corresponding rapid battery technology deployment raise concerns related with broader and more transcendent aspects of sustainability, including:

- **evaluating the impact of swift technological advancement on raw material source countries and their relationship with major consumers**
- **evaluating whether the current development paths and consumption levels can be sustained globally while respecting planetary boundaries and sustainable development goals**.

The TF SSH has the objective to go beyond a pure technology focus in sustainability, aiming to understand the role of technology in patterning society – **both how such technology shapes society and society shapes such technology**. The TF does not consider batteries just for their own sake, but for their role in making society better i.e., less emissive, less environmentally destructive, fairer in energy use, but also ensuring that the lives of those affected by battery technology along its entire value chain and lifecycle are considered. This includes avoiding net negative designs and embrace net positive, where the calculus involves social concepts such as justice, inclusion and empowerment as

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well as technical, environmental, and economic ones. In this context, a "net negative" design refers to technology or solutions that, when considering their entire lifecycle and value chain, have an overall negative impact on society and the environment.

Including SSH disciplines and domains is the way of identifying and characterising concepts relevant for understanding the role of technology in patterning society**.** In consequence, the thematic scope of the TF SSH overlaps with the TF Sustainability, including aspects of **foresight, of ethics and global supply chains, drivers of battery demand, global equilibrium models, and global distributional justice**. SSH can help with styles of innovation, appraisal of design options, understanding the contextual nature of spaces where batteries might go and what alternative designs might open up other opportunities and close down otherwise unnecessary risks. Furthermore, SSH contributes to identifying both evident and latent risks and threats, extending its benefits beyond innovators and manufacturers to encompass broader societal implications. Through its insights, SSH aids in enhancing governance mechanisms and promoting equity.

The present position paper charts the scope and calls for outlining a research agenda through the TF SSH, with the aim of giving SSH questions, especially the non-technical aspects of battery deployment, a higher visibility and relevance to the wider battery sector. **It identifies research needs for understanding how to reduce our demand for batteries and create acceptance where they are truly needed. Additionally, it recognises the necessity for shifts in habits or consumption patterns and investigates the influence of design on consumption behaviours.** By identifying how and where batteries can play a socio-technically optimal role, the TF SSH will generate impact by charting long-term viable and desirable development or deployment paths, widening the current technology-focused view towards envisioning a sustainable global battery economy. It will foreground the social purposes and benefits that current battery designs de facto have for society and explore design options in novel ways by seeing them equivalent to other (more consumption-oriented) sustainability measures, requiring interdisciplinary research projects.

This includes**:**

- **designing narratives for different types of actors**
- **creating storylines for the battery sector as a whole, with a global sustainability perspective**
- **defining the societal role of storage as a service and the most beneficial way of deploying it.**

As such, the position paper should feed into European, national and regional funding programs and research agendas by highlighting research needs for SSH disciplines, closing gaps that the technology-centred focus of the other TFs and WGs leave open and contributing to all-embracing sustainability guidance of the battery sector.

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2 CONNECTIONS TO WORKING GROUPS & TASK FORCES

Launched in 2016, the SET Plan's battery initiative is executed by Batteries Europe, the tech hub of the European Battery Alliance, which has been receiving backing from the European Commission since 2019. Originating from SET Plan action 7, which focuses on competitiveness in the global sector and e-mobility, Batteries Europe has evolved significantly. The initiative incorporates many of the original battery working group's experts and has welcomed numerous new stakeholders from industry, research, and national backgrounds.

The integration and collaboration among various Working Groups (WGs) and cross-cutting Task Forces (TFs) within Batteries Europe serve as a cornerstone for advancing battery technology and innovation. Overlapping areas between different WGs and TFs not only encourage interdisciplinary exchanges but also foster innovative solutions, enhancing the overall impact of the groups' work.

2.1 Working groups

The six WGs align with six research and innovation domains essential for establishing a competitive and sustainable European battery industrial manufacturing base. Within each of the WG focused on a distinct segment of battery value-chain, broader societal impacts -SSH overlaps- are identified below.

2.1.1 WG1: New and Emerging Technologies

Skill development: The introduction of new technologies may necessitate training and upskilling for workers to operate these advancements.

Job displacement: The adoption of emerging technologies might lead to shifts in labour demands, potentially affecting job stability and displacement.

2.1.2 WG2: Raw Materials and Recycling

Resource governance: Ensuring responsible and ethical sourcing of raw materials, implementing sustainable mining practices.

Community engagement: Involving local communities.

2.1.3 WG3: Advanced Materials

Health and safety: Considering the potential health and safety risks associated with the production and handling of advanced materials, implementing measures to protect workers.

Technology Access: Addressing potential disparities in access to advanced materials.

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2.1.4 WG4: Cell Design and Manufacturing

Labor conditions: Ensuring fair and safe working conditions in manufacturing facilities, addressing issues such as working hours, wages, and employee well-being.

Supply chain transparency: Promoting transparency in the supply chain, ensuring ethical practices.

2.1.5 WG5: Mobility Applications and Integration

Accessibility and urban planning: Addressing social equity concerns related to the accessibility of mobility solutions across different socioeconomic groups. Considering the social impact of mobility solutions on urban spaces and communities, issues related to congestion and public infrastructure.

2.1.6 WG6: Stationary Applications and Integration

Energy access: Ensuring that stationary applications contribute to improved energy access, energy poverty issues.
Community Resilience: Assessing and enhancing the resilience, reliability of communities where stationary applications are deployed, community engagement.

2.2 Task forces

The cross-cutting TFs were established to enhance cooperation among members of the WGs in transversal topics, broad-based thematic areas relevant across the entire value chain. These Task Forces are designed to address key challenges in these areas, offering advice and assistance to the WGs' activities.

2.2.1 TF Sustainability

The mission of the TF Sustainability is to evaluate and to pinpoint potential impacts of battery technologies on the environment and on resources. It considers environmental, economic and social impacts, the latter via the application of social life cycle assessment (LCA). In general, LCA approaches are technology-focused, with social LCA incorporating the use of materials and associated added-value (or working hours) with sector-specific 'social risks' (e.g. risk for child labour mainly related to raw material extraction). Therefore, they identify environmental, economic or social 'hotspots' along the value chain, without including broader social aspects of acceptance, justice, consumption patterns, sufficiency, which are foundational to SSH approaches. High potential for synergies exists between TF SSH and TF sustainability, with the TF SSH tackling questions that go beyond the horizon of the TF sustainability, while requiring input and exchange with it.

2.2.2 TF Education and skills

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The latest [Batt4EU/Batteries Europe SRIA](#) highlights significant advancements in fostering new job opportunities within the battery value chain, notably through the identification and implementation of current educational initiatives. In addition, European requirements, emerging job roles, learning goals, and educational strategies for the industry are being analysed and classified. Numerous programs are underway across Europe to educate individuals and prepare future workforce through education, skill development, and retraining of workers.

By integrating battery-related content into school curricula, the sector not only educates young individuals about the importance and benefits of batteries but also fosters an early appreciation for sustainable energy solutions. The TF is putting forward the message of batteries as a net good for society, highlighting their role in providing sustainable, interesting, and well-paying jobs. Public learning labs and awareness campaigns can further demystify battery technologies, encouraging public engagement and support. Through these educational initiatives, the TF can leverage SSH to understand and enhance the societal impact of the battery sector, ensuring its development aligns with broader societal values.

2.2.3 TF Safety

Battery safety issues are crucial for gaining public trust and confidence in the transition to new energy systems. Ensuring that batteries are safe and do not harm the environment or the health of workers and users is vital for their widespread acceptance. Addressing these concerns is not only about preventing physical harm but also about fostering public awareness and trust in emerging battery technologies, which are essential for the successful deployment and adoption of these systems in society.

2.2.4 TF Digitalisation

The digitalisation of the battery industry holds potential social impacts too. Positively, it supports sustainability and resource availability, enhancing societal resilience and security. However, it also introduces risks like data breaches and infrastructure disruptions, which can lead to economic losses and affect daily life. These challenges highlight the need for strong cybersecurity, ethical practices, and inclusive policies to ensure the benefits of digitalisation are broadly shared and its risks are mitigated.

2.2.5 TF Hybridisation

This TF is dedicated to exploring energy storage applications that integrate two or more technologies and systems, with at least one involving batteries. The integration of batteries with other energy storage technologies yields innovative solutions that have the potential to reduce costs, enhance reliability and flexibility, and improve sustainability performance when compared to single-energy storage systems. These hybrid energy storage system applications find utility across various sectors, including industry, transportation, the energy grid, and buildings. Consequently, the scope of this TF is broad, with its alignment with the TF SSH primarily directed towards issues akin to those encountered in stand-alone battery applications. These may include considerations spanning social, economic, and environmental impacts on a larger scale, such as recyclability or disposal post-system lifespan, as well

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as issues linked to mining activities (e.g., community displacement, health hazards, land loss et al.). Additionally, concerns at the user level, such as safety, the presence of PFAS substances, operational aspects, recycling, and disposal, are also pertinent[2].

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3 SSH RESEARCH ON BATTERIES: THE STATE OF THE ART

Highlights of this part:

- *Systematic mapping reveals SSH research on batteries predominantly focuses on economic and business aspects, with substantial input from sociology and political science.*
- *Theoretical and analytical approaches within SSH offer insights into potential risks and opportunities in battery development.*
- *Various SSH and interdisciplinary frameworks exist that can effectively guide battery development and deployment.*
-

3.1 The scope of SSH

There is no single definition of what is included in the spectrum of the SSH disciplines. Fundamentally the framing of SSH here covers disciplines outside of STEM (Science, Technology, Engineering, Mathematics) disciplines. This represents a full spectrum of disciplines within the SSH, Education, Business, and Law sectors, drawing from the UNESCO International Standard Classification of Education (ISCED 2011), this itself being a reference point for the European Union Horizon Europe Programme[3]. Box 1 sets the SSH disciplines out in full form.

Box 1: The scope of Social Science and Humanities (SSH), defined by UNESCO

Social Sciences, Education, Business, and Law:

- Social and Behavioural Sciences: Encompasses studies in economics, the history of economic thought, political science, sociology, population studies, cultural anthropology (excluding physical anthropology), ethnology, future studies, psychology, human geography (excluding physical geography), peace studies, conflict resolution, and human rights.
- Education Science: Focuses on the development of curricula for both non-vocational and vocational education, strategies for educational evaluation and policy, and the pursuit of educational research.
- Journalism and Information: Includes disciplines such as journalism, the science of libraries and museums, documentation, and archival science.
- Business and Administration: Covers areas like merchandising, marketing, salesmanship, public relations, property management, finance, banking, insurance, investment theory, accountancy, audit practices, business management, and administration for public and private sectors.
- Law: Encompasses legal studies, the philosophy of law, and the historical study of laws.

Humanities and the Arts:

- Humanities: Encompasses religious studies, theology, studies in foreign cultures and languages (including those no longer spoken), literature of both ancient and modern languages, area

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studies, indigenous languages, colloquial and dialect literature, interpretation, translation, linguistic studies, comparative literature, history, archaeology, philosophy, and moral philosophy.

- Arts: Includes the fine arts, performing arts, visual and audio-visual media arts, design, and crafts.

3.2 Research and concepts from SSH in batteries: an overview

To understand what research to date has been done in SSH on batteries within the restricted timeline and resources of the task force, **a brief, systematic mapping was undertaken leveraging the power of the online abstracting database Scopus.** Despite its recognised limitations, mapping the SSH literature this way allows for a snapshot of the kinds of research that have been developed over the last decade or two, providing an understanding of where the main gaps and focus are. For more detail on the method used to arrive at the mapping, see *Annex B*. In the process of mapping the research, groupings of SSH disciplines emerged into categories that reflected identifiable clusters of research. The final categories are shown in *Table 1* together with the number of instances that disciplinary perspective was present in the examined dataset. Overall, 153 different papers were identified, and each was coded for the presence of disciplinary areas as per Table 1. Since a paper can have more than one of these areas, the counts in Table 1 add up to 193 instead of 153.

Disciplinary areas	Count	Proportion
Economics, business & administration	86	56%
Sociology, anthropology, human geography & related	48	31%
Political science and international relations	31	20%
Psychology and ergonomics, human factors and related	16	10%
Law, history and related	8	5%
Other	4	3%

Table 1: The six SSH categories used to code the academic SSH research on batteries and the proportion of the corpus codable by each category

Table 1, unsurprisingly, shows that the vast majority of SSH research on battery uses (to one degree or another) an economics and/or business-related lens. The 48 papers with a sociological approach formed the second most numerous category. If the sociological aspect is combined with political science, then a similar number of papers are identified as economic research, revealing an overall balance between economic and non-economic research on batteries. Further, a minority number of papers (13%) were categorised as using modelling or simulation one way or another, reflecting an important corpus of research that likely forms an interface with the wider STEM research in this area. Modelling is not included in the list of disciplines as it is qualified in this exercise as a methodological rather than a disciplinary area.

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There is a clear emphasis here on the Social Science aspects of SSH which may in part be due to the search protocol *(see Annex B)* At the same time, there is a range of disciplines within SSH for which research on batteries seems unlikely (e.g. languages). The 153 papers therefore represent the core focus of batteries-related research in the SSH to date (at least in Western/Global North academic communities). Mapping research in this way provides insight into the range and value of SSH for batteries, as well as allowing a strategic analysis of research gaps which are explored in Section 6 of this Position paper.

An alternative way to explore SSH's value is to examine how theoretical, conceptual and analytic approaches or methods have been developed that can reveal aspects of battery development – risks and opportunities – that might otherwise remain hidden. Now, attention is directed towards examining the potential contributions of SSH to the understanding of what constitutes effective battery technology in Europe.

3.3 Existing SSH theories, frameworks and methods applicable to batteries development and deployment

The above analysis employs systematic mapping of academic research to offer a platform for reflecting on where SSH could contribute more and where the research centre of gravity seems to reside. Next, the expertise across the TF is made use of to identify the kinds of ideas or approaches prominent in SSH for their potential to provide practical and impactful insight for Batteries Europe.

What role can SSH play in getting the best of batteries for society? Here, we consider ways of appraising the design, use and deployment of batteries, bring SSH questions to the fore. The focus here is on developing a *normative* stance (that is, thinking how and where batteries *should* be designed, deployed, and used) rather than a purely critical-descriptive approach (that is, identifying the problems with the way things are). In part this is due to the need to be compatible with the other normative approaches that are adopted by the more technical TFs and WGs as each of them, in their way attempt to set out what the 'best' batteries for Europe are.

Work by SSH scholars tends to emphasise certain concepts as central to technology transitions and development. These include inclusion and participation in decision-making, justice and equity in process and outcome and enabling resilience by supporting the vulnerable[2]. The challenge for SSH scholars lies in ensuring that these concepts are approached in ways that allow them to effectively influence and integrate with the existing processes of extraction, innovation, design, manufacturing, and distribution for batteries. Box 2 highlights some established approaches that represent ways of thinking, methods and frameworks to bridge that gap developed by SSH scholars. One approach affiliated with SSH that stands out as the most obvious is economics[3,4]. We note an example of such approaches in Box 2 as a further strategy to find ways of opening up how 'good' battery designs and strategies are appraised and enabling better connection with a wider set of SSH ideas and methods.

Box 2: Theories, frameworks, and methods from SSH to inform and guide battery development

Energy justice[5,6] highlights and structures key concepts from justice and ethics in a way that enables consideration of choices in the design and deployment of resources, these comprise distributional, recognition, and procedural justice[7].

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Responsible research and innovation[8,9] have been taken up by research funders in the EU and UK and by industry[10] as a means of driving forward a more societally sensitive approach to innovation. RRI emphasises anticipation, inclusion, reflexivity and responsiveness in the process of technology development and in appraisal of technology choices.

Value sensitive design[11] and **safe and sustainable by design**[12] provide approaches for thinking through how the engineering design process of new technologies can be explored to reveal implied values and determine if the values embedded are the ones intended or desired.

Recent work by Jenkins et al[13] has sought to **consolidate and combine** the above three concepts, advancing thinking in this area.

Social Life Cycle Assessment[14,15] s-LCA aims to incorporate social elements into the more commonly environmental focused method for assessing technologies and processes across their lifecycle.

Doughnut economics[3] is an appraisal framework to systematically consider macroeconomic elements not just in terms of GDP but in a range of other social and environmental units.

The approaches above provide frameworks and concepts that aim to bring social concepts to bear on choices around battery development and deployment. Other work in SSH identifies methods for collaborating across disciplines and communities for enabling the kinds of inclusive, participative and just goals embedded in the frameworks above.

Multicriteria mapping[16,17] aims to open up questions of risk in new technologies and reconcile different perspectives and values. This technique is different to multi-criteria decision analysis by embedding more open, unconstrained approach to incorporating criteria for appraising options.

Transdisciplinarity[18] and **participative systems mapping**[19] both provide guidance for how to integrate ideas across different expert and indigenous or local community knowledge – either at the team level or decision-analytic level using systems approaches.

The approaches in Box 2 provide a starting point for considering how concepts and analysis from a range of social sciences can be brought to bear in the context of the choices faced in Europe when investigating the role of batteries in supply chains and product development to serve different purposes in society[1]. Each approach could play a significant role in various aspects, whether in the management of battery technologies, the design of systems, or the regulation of supply chains. These approaches can be evaluated for their ability to align or integrate with the concepts and methodologies typically used in engineering and economics, making them well-suited for the interdisciplinary and transdisciplinary efforts required by a platform like Batteries Europe.

[1] Some other SSH concepts and approaches that can be useful in this context include, for example, political sociology, innovation studies, social shaping of technology, actor-network theory, critical realism, social practice theory, social acceptance theory.

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4 AN OUTLINE FRAMEWORK FOR INTEGRATING SSH INTO THE BATTERIES EUROPE AGENDA

Highlights of this part:

- *A blueprint framework has been developed to explore the intersection of SSH, and battery technology, focusing on analysing their components and lifecycle stages.*
- *Mapping SSH research onto the battery lifecycle reveals a focus mainly on economic and sociological aspects, with substantial insights into raw material extraction and the end-of-life phase.*
- *Significant research gaps have been identified in the transport and distribution stages of the battery lifecycle, highlighting the need for broader SSH engagement.*
- *The adoption of a product lifecycle framework proves effective for integrating SSH perspectives, offering a comprehensive view from raw material extraction to disposal and recycling.*

The overarching goal of the TF SSH is to inform and influence Batteries Europe platform stakeholders of the benefits and possibilities of the SSH research in developing a competitive value chain for batteries in Europe and beyond. The challenge that SSH faces here is in finding clear points of purchase with the current work and perspective taken in BE while neither overlooking the critical role (as in both important and challenging) SSH plays in addressing societal outcomes from technology development, nor cherry-picking only the more aligned research approaches. In addition, the TF SSH has a responsibility to represent the broad array of disciplinary perspectives that scholars across these fields bring. It is a challenging square to circle. Our initial approach to addressing this is to provide an outline framework for how SSH and batteries might intersect. We build this initial framework by considering the ways SSH and batteries can be understood or broken down into component parts.

4.1 A frame for SSH: the disciplines

As a starting point we build on the prior breakdown of SSH into constituent parts, it's recognisable disciplinary components as set out in *Section 3.* In doing so, this approach enables a more direct identification of scholars from specific disciplines who could be engaged in research and innovation related to Batteries Europe. However, as we have seen in practice, the disciplinary names can be problematic and sometimes unsuitable for certain tasks, such as mapping academic research. Nevertheless, they provide a starting point for a framework which is a central task of the TF SSH.

4.2 A frame for batteries: product lifecycle

The other aspect of the framework is in relation to batteries themselves. Again, we face choices in breaking down the concept of a battery in a way that opens up opportunities for SSH input while also identifying commonalities with the ways batteries are understood in other TFs. The initial choice here is to use a standard product lifecycle approach to defining the aspects of batteries to which SSH can

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be seen as relevant. This, particularly, complements discussion on the LCA methodology in the Sustainability TF Position Paper. It also facilitates the application of a structured and inclusive framework to batteries, enabling a description that more closely matches the concepts of social sustainability. At the same time, a product lifecycle perspective doesn't easily capture other important aspects related to batteries, but which sit just outside or adjacent to it: workforce development, innovation processes including identification and characterisation of use cases and so on. These aspects are clearly important to TF SSH. For now at least, the main way of addressing these is via engagement with the other TFs (see Section 2 of the paper) and WGs.

One advantage of using a product lifecycle framework is that it includes the use of a battery (which is an obvious contact point with SSH) but as simply one stage among others - opening up opportunities for wider SSH engagement in batteries. It is important to remember that a battery's life cycle involves distributed communities of workers and users, from the extraction of raw materials through manufacturing and distribution, to end-use, reuse, recycling, and disposal. Understanding what a battery 'is' requires considering these aspects, and it is the role of the SSH community to represent these wider communities. The other advantage of the lifecycle approach is that it has a direct and obvious connection to forms of appraisal in engineering and product design that help define what 'good' batteries might be – life cycle assessment. Life cycle assessment is an established approach, and with it the more recent forms of social life cycle assessment provide the basis for an analytic integration of engineering analysis and social ontology. Further, the emergence of social LCA (s-LCA, as noted in Box 2) means the wider SSH community has a ready-made platform to explore how a wider SSH insight can be integrated into a relatively technical appraisal approach. We see emerging examples of such social LCA in the case studies (Section 5). LCA as a method has multiple advantages but also some limitations compared with other frameworks which might also be useful and relevant here. These limitations include context specificity, data availability, time- consuming process and cost. Importantly, s-LCA has its own limitations: it generally does not directly provide information on whether a product should be produced or not, doesn't explore behaviour vs function and the geographical variety is limited[20] .

4.3 Alternative battery framing

Alternatives for representing batteries in the context of Batteries Europe - where the goal of the overall platform is "to develop and support a competitive battery value chain in Europe" - might focus more on value chain components or innovation stages (e.g. technology readiness levels[21]). These would potentially fit more directly onto the core goals of Batteries Europe which are about innovation and value chain enhancement. However, one argument against that is that these lenses are too narrow and may reduce the opportunity for an effective SSH input. For now, a lifecycle framing of batteries seems most useful or the least problematic.

4.4 Alternative SSH framing

What other ways are there of framing SSH? One alternative is to consider the key concepts central to SSH research. We identified some key concepts earlier in Section 3 (concepts such as inclusion, participation, justice and equity). However, this can be readily expanded to a much broader list

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including power, structure, agency, practices, behaviour, habits, capital, networks, relations, governance and so on. This expanded list predominantly emphasises concepts from sociology, anthropology, and psychology. However, it notably omits key areas like acceptance, place, policy, and entrepreneurship, which are central to human geography, political science, and economics, and could be integrated as well.

The challenge lies in determining methodological robustness, given the lack of a universally accepted structure or a definitive criterion for completeness. It's conceivable that the efforts of TF SSH alone may suffice, rendering additional frameworks unnecessary, or that various frameworks might be needed for different objectives. At this stage, TF SSH's goal is to initiate a discussion and foster exploration, employing the most suitable methods for the objectives that resonate most within the Batteries Europe community.

4.5 Mapping SSH research onto the outline framework

This initial outline framework for SSH in batteries can be seen as a **stimulus to SSH community engagement**, enabling a mapping of who is engaged in battery-related research, which disciplinary perspectives are missing, and provide **license for future engagement to explore the questions arising**. Table 2 shows the value of this framework by taking the SSH academic research mapping in Section 3 and applying lifecycle stage coding to each paper. Note that more than one lifecycle stages may be apparent in one paper, and for some where more than 3 stages are present (especially those using s-LCA) they were coded as cross-cutting.

Briefly, some patterns are observable from this initial coding of the research. Most SSH research on batteries centres around the economics (and related) approaches to battery use, followed by more sociological (and related) studies of use. Raw material extraction features significantly in SSH research mainly (geo)political-economic but with a clear if small corpus on anthropological issues related to extraction. Finally, economic studies of end of life (and associated recycling approaches) feature alongside psychological and human factors related research. **There are clearly gaps both in the lifecycle stages – transport (of materials) and distribution (of products) has limited SSH inquiry.** Perhaps most significant is the lack of political science (and related) studies on battery distribution given how significant this topic might be for Batteries Europe work.

	Economics	Sociology	Pol. Sci.	Psychology	Law	Other	Totals	%
Raw mat.	**20**	**12**	**19**	0	1	0	54	35%
Transport	2	0	2	0	sn0	0	4	3%
Production	**13**	5	7	0	0	0	25	16%
Distribution	4	6	0	2	2	0	14	9%
Use	**38**	**29**	5	**11**	3	1	102	67%
End of life	**17**	6	1	5	0	2	37	24%

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X-cutting	6	2	5	0	4	1	21	14%
Totals	100	60	39	18	10	4		
%	65%	39%	25%	12%	7%	3%		

Table 2: Showing the number of SSH-coded papers also coded for the life-cycle stage they principally focus on

The mapping above illustrates the potential value of the outline framework and provides insight for a key TF SSH output – to inform future research priorities. We return to these below. Before doing so, some key, illustrative research will be considered, showing how collaboration with stakeholders in battery technology can be facilitated by SSH. In part this helps ensure that the TF SSH contribution is pragmatic rather than abstract, but also provide stimulus to the wider SSH community to build on this work, gaps and issues they reveal. Further, the very existence of the outline framework here can be seen as just such a friendly 'provocation' to the SSH community to build on the early groundwork TF SSH has achieved in this short time.

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5 CASE STUDIES

Highlights of this part:

- *Case studies illustrate the application of the SSH framework in enhancing societal relevance within battery and renewable energy projects.*
- *Insights from existing research, such as social risks, public acceptance, and policy drivers, offer valuable guidance for future battery projects.*

In this section, the practical applications of the SSH framework are explored, showcasing how it enhances the societal relevance in battery and renewable energy projects. Through a selection of few **examples and case studies, the applications of the SSH framework are illustrated, to ensure that battery projects not only achieve technological milestones but also resonate with and benefit society**. This exploration includes the application of the SSH framework in battery technology projects, highlighting how social life cycle assessments and ethical considerations inform and shape battery production and usage.

Additionally, the application of the SSH framework in renewable energy technology projects is provided, emphasising the importance of social acceptance and policy frameworks in the successful integration of these technologies into society.

1. **Social Risk Assessment of BESS Life Cycle**: Koese et al. (2023)[22] conducted a social LCA on vanadium redox flow and lithium-ion batteries, utilising UNEP/SETAC guidelines and the PSILCA v.3 database. Their findings highlight the primary social risks associated with battery life cycles, particularly in raw material extraction and chemical sectors, with workers being the most adversely affected stakeholder group. This study underscores the necessity of addressing social risks early in the battery's life cycle to mitigate adverse impacts on vulnerable communities and environments.
2. **Social Risk Profile of LFP Battery**: Research by Yi Shi et al. (2023)[23] on lithium iron phosphate (LFP) batteries through social LCA identifies significant concerns regarding corporate social compliance in the production of LFP batteries. This study contributes to the ongoing public debate on the ethical implications of battery production, emphasising the need for greater corporate responsibility and transparency in supply chains, particularly in China, Japan, and South Korea.
3. **Social Acceptance of Large Battery Storage[24]**:An examination of the societal acceptability of large stationary battery storage systems reveals that public acceptance is significantly influenced by the visual impact, location, and design of battery storage installations (Baur et al, 2023). An online survey method was used to gauge perceptions, indicating that aesthetics, environmental integration, and community engagement play critical roles in fostering societal support for renewable energy storage solutions.
4. **Ethical Considerations of Raw Material Extraction**: "*Cobalt Red: How the Blood of the Congo Powers Our Lives*" by Siddharth Kara[25] provides an ethnographic insight into the ethical concerns surrounding cobalt extraction in Congo, essential for mainstream lithium-ion batteries. Similarly, *Voskoboynik and Andreucci*[26] explore how lithium mining is presented as necessary to mitigating climate change in industrial settings providing a means to reflect on what kind of value is being generated for whom in the battery value chain.

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6 RESEARCH GAPS, POLICY IMPLICATIONS AND RECOMMENDATIONS

Highlights of this part:

- *Mapping SSH batteries research shows a gap in disciplinary perspectives at different lifecycle stages, highlighting both specific and potential unseen gaps.*
- *A categorised list of SSH-focused research questions aims to bridge these gaps, fostering SSH contributions to battery research through collective expertise.*
- *The questions we provide are not exhaustive but pivotal for exploring SSH priorities and concepts within battery research.*
- *Advocating for a transdisciplinary approach, integrating SSH and STEM fields is essential for effective research and innovation in batteries, as recommended by the TF SSH.*
- *The TF SSH's exploratory work lays foundational steps for structured engagement between the SSH and STEM communities in European battery research and innovation.*

As Europe accelerates its transition towards a more sustainable and electrified future, **the integration of SSH perspectives ensures that policies, innovations, and market strategies are rooted in societal needs and values, fostering public acceptance, and promoting responsible innovation.** By examining the cultural, social, and political dimensions of battery technology, SSH research can contribute to more inclusive and equitable energy systems, identify potential social barriers to technology adoption, and facilitate dialogue between stakeholders to align technological advancements with European societal goals.

6.1 Research gaps and questions

The mapping of the SSH batteries research in Section 4 reveals one kind of gap – that of the disciplinary perspectives applied to specific lifecycle stages of batteries. This leaves open what specific questions might be asked in relation to those gaps as well as whether there are other kinds of gaps – gaps important for unlocking SSH value to batteries that are invisible with the outline framework described above. As a part of the TF SSH work, **we collectively developed a set of questions building on the individual expertise in the group to provide a categorised list of SSH-focused batteries research questions.**

6.1.1 Sustainability and Ethics

- How can the traditional *three-dimensional model of sustainability* (environmental, economic, and social) be critically evaluated and potentially redefined to more accurately reflect the complexities and interdependencies of sustainable practices, particularly in the context of economic and social dimensions?
- How do the *ethical considerations of deep-sea and Antarctic mining* for battery materials, particularly in high biodiversity or untouched areas, influence decision-making processes, and

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what frameworks can be established to balance resource extraction with environmental conservation and social responsibility?

- What strategic approaches and policy frameworks are essential to achieve a *just transition* to *a low carbon economy*, considering the Sustainable Development Goals (SDGs), and how can these strategies ensure equitable outcomes for all stakeholders involved in the lifecycle of battery storage systems?
- How do batteries contribute to well-being and life satisfaction? How much is battery needed for 'living a good life', and how much would be possible under a global perspective, respecting planetary boundaries and social minimum (sufficiency) requirements?
- How can *battery due diligence policies* be effectively designed and implemented to address social risks, including the protection of human rights, community life, indigenous peoples' rights, child protection, gender equality, and labour rights in accordance with international human rights law and ILO conventions related to the EU Batteries Regulation.

6.1.2 Engineering and Design Perspectives

- How do *battery design engineers* perceive and understand batteries? What reference frameworks do they employ, and how could the integration of SSH concepts alter these frameworks and their understanding?
- What are the constraints and priorities that shape the current *design and innovation strategies in the battery sector*? Who benefits or suffers from these strategies, and what viable alternative approaches can be proposed?
- What *unique characteristics and capabilities* do batteries possess when considered as independent units, and how do these attributes differ from their roles in electric vehicles and photovoltaic systems?

6.1.3 Policy, Socio-Economic Impacts and Geographical context

- In what ways do *policymakers conceptualise batteries*, and what explicit or implicit narratives guide their understanding? Are their perspectives influenced by considerations of sectoral growth, environmental limits, or economic models like the *doughnut economy*?
- What are the *socio-environmental impacts* of the expanding battery industry and rare mineral mining in Europe, and how do these developments affect land use, local communities, and environmental risk management?
- How can SSH be more effectively *integrated into battery-related policies* to address issues of *resource ethics, material neocolonialism, and broader social impacts*, and what lessons can be drawn from the oil sector to anticipate and mitigate similar challenges in the battery industry?
- How do variations in *public policy and other contextual factors* across different countries influence the deployment and effectiveness of Battery Energy Storage Systems (BESS), and what can be learned from comparative analysis to guide future policy and technological advancements in energy storage?
- What SSH aspects are relevant to take into consideration during the *selection process for battery manufacturing* plants, and how do these aspects influence the design criteria for new battery developments?

6.1.4 Usage and Application in Society

- What are the *diverse and adaptive uses of batteries within household settings,* such as their role in car-to-home energy systems or in domestic heating systems when integrated with heat-pumps, as

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identified through ethnographic investigation? Does this lead to the expected empowerment of consumers towards prosumer, actively participating in the electricity grid?
- What are the *social and cultural ramifications of mining activities* for battery materials, with a specific focus on the extraction of rare earth minerals in Europe and other areas?
- How do *towns that rely on the establishment of battery factories* for economic revitalisation manage their expectations and cope with the outcomes when such industrial projects are unsuccessful or unfeasible? How do /can towns deal with possible local environmental impacts of such factories?

6.1.5 Environmental and Industry Implications

- What are the *rebound effects* associated with the deployment of batteries in various sectors, and how do these effects influence the overall environmental and energy efficiency gains promised by battery technologies?
- What are the *key drivers behind the export and informal recycling of batteries*, and what effective remedies can be implemented to address the associated environmental, social, and economic challenges?
- What are the *potential long-term impacts of the global transition* to battery-based systems on the battery value chain, and how can foresight studies inform strategies to optimize benefits and mitigate negative outcomes across environmental, economic, and social dimensions?

6.1.6 Comparative and Future-Oriented Studies

- How can an *inter- or transdisciplinary evaluation framework* be developed to assess battery innovation and utilisation, which includes social and life cycle assessment methods?
- What are the critical *environmental, social, and economic impacts of establishing battery factories*, and how can these insights inform the strategic planning and assessment processes for future battery industry projects in Europe?
- How do variations in public policy and other contextual factors across different countries influence the deployment and effectiveness of BESS, and what can be learned from comparative analysis to guide future policy and technological advancements in energy storage?

These sets of questions are not meant to be seen as exhaustive, systematic or even necessarily strategic (though some do directly address gaps identified in Table 2). It represents important areas of inquiry for SSH scholars in this area, based only on SSH-rooted priorities and concepts. At the same time, a key part of developing an effective programme of research and innovation is the integration of perspectives across SSH and STEM – and ideally, inclusive of perspective outside of academic disciplines – so truly transdisciplinary. We expand on this point below as part of the research policy recommendations arising from the TF SSH.

Below we present three perspectives from TF SSH members:

Box 3: Beyond social acceptance

"Social acceptance of batteries and connected mining industries is a tricky term, as it implies that battery production is legitimate per se. Deeper insights into complex social and natural assemblages are needed. As the battery industry and mining for rare minerals are increasingly established in Europe, so are the conflicts and challenges connected to land use, risks, and pollution."

[Zane Datava, NTNU, TF SSH Member]

Box 4: Unintended consequences

"Seemingly empty nature is being taken over and used for industrialisation in the name of a greener future. However, we must question how green this future is. A growing town, heavy traffic, construction sites, demographic tensions, and pressure on services may affect the citizens in these developing areas. Moreover, despite their low-carbon ambition, large-scale developments paradoxically contribute to an increase in carbon emissions and loss of nature. These developments are embraced simultaneously and quickly, exacerbating the negative consequences. A thorough examination of the areas for potential battery factories is needed before the implementation of the projects. As a pioneer in EV adaptation and a thriving battery industry, Norway is an example of conflicts in implementing the mining sites (Førdefjord, Repparfjord), protests and tensions in renewable energy sites areas (Fosen case, Trøndelag) and the collapsed industry hopes when the imagined battery factory is failing, and the production is moved abroad (Mo I Rana case)."

[Zane Datava, NTNU, TF SSH Member]

Box 5: Benefits of international comparisons

"Comparative analysis – both statistical studies and comparative case studies – allows for examining the effects on battery electric storage systems (BESS) of variations in public policy and other variables, for learning lessons between cases. It will be central to the advancement of knowledge of public policy in this domain. To date, much of the policy-related literature on storage and the deployment of BESS has had a single-country focus. Cross-national comparative studies are rare, and have examined the role of storage technologies in the decarbonisation of the North American countries and its dependence on resource availability, technology costs, and public policies have sought to examine the case of Australia in respect of batteries and shaben gas storage and drawing lessons from several 'leaders' on storage (California, Texas [USA], Germany and Japan)."

[Marc Ayoub, University of Galway, TF SSH Member.

[Conor Little, University of Limerick, TF SSH Member]

6.2 Policy implications and recommendations

The work of the TF SSH has been exploratory and aimed to lay the first foundations for a more structured engagement between the SSH and the STEM communities researching and innovating batteries in Europe. Hence, the policy recommendations are primarily addressing the evident capacity gaps identified through the preliminary assessment of SSH's role in battery research. Some clear challenges are present in the state of the art and the consequences of mapping the research capacity in the outline framework:

1. There is very limited research from or in the SSH approaches that focus mainly or exclusively on batteries.
2. What SSH research there is, tends to focus only on the use of batteries and to some extent the mineral extraction for battery manufacture.
3. The majority of SSH research is mainly or partly economics-related research. Other disciplinary perspectives are potentially underserved, especially those from humanities.
4. There is limited research that combines SSH and STEM perspectives effectively, and even relatively advanced methods such as s-LCA have clear limitations.
5. There are important SSH-related research questions that need addressing, but there is no structured forum or process to establish them across the SSH community.
6. The wider impacts of establishing a competitive value chain in Europe, particularly in the context of Widening EU countries, as well as its impacts beyond Europe (see Box 6), have not been thoroughly explored.

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Box 6: Battery value chain considerations beyond EU

The impact of new and sustainable battery technologies to be adopted in the EU would have significant impact in the *Global South*. The global south will be the largest producer and consumer of batteries worldwide. Hence it is important to think of an approach that is inclusive and equitable when it comes to new, sustainable batteries for Europe. More specifically there would be political, economic, social, technical, environmental and legal issues involved.

Political: Political forces in the global south are currently locked in a debate that involves negotiation with the developed countries for more time and financing to help them make a just and green transition. Such discourses negate the fact that green technology adoption is a global need today. There is a role for EU to build consensus among political parties in the global south about battery technology and adoption. Such consensus can help parties rise above electoral compulsions and bring in new laws for quicker adoption of upcoming technologies. To that extent, the EU can play a pivotal role by initiating dialogues with its stakeholders in the global south.

Economic: Companies manufacturing and using batteries have ambivalent attitude towards sustainable technologies. This is primarily driven by 1) the need for short term revenue and profit generation and 2) future strategies to adopt new battery technologies. The actual and emergent strategies will create tension in actual marketplace introduction and adoption of green technologies. Batteries Europe and similar initiatives should create pilot cases for global south industries and suggest incentives (rather than penalties) for early and easy adoption by exporters and market leaders. We can explore creating a separate project targeted at the global south for achieving this.

Social-ethical: The social cost (including health cost) for using unsafe and hazardous products and processes involved in battery value chain is highest in the global south. The battery chain involves work by the poor and marginalised groups who are largely unorganised particularly in the post-use phase. It is necessary to a) map vulnerable groups involved in the battery industry, b) provide them basic social security through provision of identity cards, health insurance and vocational training. Corporate social responsibility funds of leading companies can be utilised for this purpose.

Technological: The technology change cycle in the global south is likely to be long and complex given the high variation in product/technology cost and preference for affordable products/services. We would need engagement with future engineers and managers through leading engineering and business schools.

Environmental: The harsh environmental impact of used batteries has maximum environmental impact in the global south. We would need innovations for extending life of batteries but also large-scale campaigns to create awareness about the need to transition to new and safer technologies.

Legal: The relevant national standards in the global south will pose a major problem in adoption, use and disposal of batteries. We would expect industry bodies to take a stewardship role in lobbying with respective committees for an urgent review and upgrade of the standards.

[Subhasis Ray, XIM University]

6.3. Research recommendations

To enhance the contribution of SSH researchers in battery research, the following recommendations propose establishing structures and funding mechanisms that support interdisciplinary collaboration, focusing on specific research gaps within battery value chain. They suggest initiating projects that broaden the scope of techno-economic considerations in battery research, fostering innovation and value chain analysis.

1. Develop structures and processes that enable SSH researchers to gain support and focus their research on batteries. This is likely to include specific funding streams but may extend beyond mere research project funding to include coordination and support actions that facilitate collaboration, visits, and centres of excellence.

2. Consider developing research project calls that aim to explicitly fill the gaps in the outline framework by naming life cycle stages. This could be prefaced by a collective of SSH scholars undertaking a deeper analysis of research to establish whether a different, more important set of gaps should be focused on, using alternative frames (see Box 2).

3. Create events, programmes of work and outlets that enable non-economics SSH researchers to work expressly on batteries, potentially starting with projects that develop and extend s-LCA approaches to take into account a wider idea of 'the social', but also to develop alternative framings or approaches, including those rooted in innovation (building on RRI) and value chain research.

4. Establish a forum for SSH researchers to collectively develop and debate key research questions in batteries research, that can inform research funding priorities across Europe.

5. Explore the potential for setting up a transdisciplinary engineering and research and innovation programme drawing on experience across Europe where similar programmes of work have been trialled in areas related to batteries.

6. Initiate a responsible battery value chain debate to critically examine and address the environmental, social, and economic implications.

These recommendations primarily focus on research policy, aimed at enhancing the capacity of SSH to provide significant and impactful insights in research and innovation

7. CONCLUSION

The Batteries Europe/BEPA Task Force on Social Sciences and Humanities has crafted a position paper that aims to bridge the divide between technological advancements in battery technology and the socio-cultural dimensions within which these technologies operate. This document not only explains the current state of 'SSH for Batteries' but also provides research policy perspective over the interplay between technology and society.

Acknowledging the limited presence of SSH experts in the battery sector, the TF underscores the necessity of integrating SSH perspectives throughout the battery technology value chain. The task force's recommendations, based on analysis of socio-technical research, advocate for the integration of SSH insights across the entire value chain of battery technologies.

The call to action is clear: stakeholders, policymakers, and industry players must adopt a "human-centric paradigm," where SSH is not peripheral but integral to technological development. By encouraging dialogue, and inclusion of the SSH agenda in innovation funding and implementation, the task force envisions a future where technological advancements in batteries are synergistic with societal progress [27].

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Research and Innovation Programme under Grant Agreement N. 101069676

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Research and Innovation Programme under Grant Agreement N. 101069676

ANNEX A – LIST OF CASE STUDIES

Battery SSH topic	Battery technology	SSH Method(s)	Conclusion(s)/ comments	Reference
Social risk assessment through the whole BESS life cycle	vanadium redox flow battery, lithium-ion battery for BESS applications	Social LCA based on UNEP/SETAC guidelines and PSILCA v.3 database	The primary social risks associated with the life cycle of batteries typically emerge during the raw material extraction stage, with additional significant risks present in sectors related to chemicals. Among the various stakeholder groups, workers are the most affected	Koese, M., Blanco, C. F., Vert, V. B., & Vijver, M. G. (2023). A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage. Journal of Industrial Ecology, 27, 223–237. https://doi.org/10.1111/jiec.13347
Social risk profile of LFP battery	Lithium iron phosphate battery	Social LCA	"The conclusions provide a core concern for the eager public discussion of LFP battery corporate social compliance"	Yi Shi, Xintong Chen, Tingting Jiang, Qiang Jin (2023). Social life cycle assessment of lithium iron phosphate battery production in China, Japan and South Korea based on external supply materials, Sustainable Production and Consumption. Volume 35, 2023, 525-538. https://doi.org/10.1016/j.spc.2022.11.021.
Social acceptance of large battery storage	Stationary battery storage	Online survey is conducted by examining the visual impact (location and design) of BS on acceptability		Societal Acceptability of Large Stationary Battery Storage Systems **https://doi.org/10.1002/ente.202201454**
Raw material	Mainstream Li-Ion batteries	Ethnography/field research		Cobalt Red: How the Blood of the Congo Powers Our Lives by Siddharth Kara

ANNEX B

It is non-trivial to find SSH literature on Scopus because the way academic papers are classified is not completely transparent, and of course the breadth of disciplines and perspectives involve is broad. What we report here is a brief overview of a relatively extensive process that sought to identify research relevant to the task force, and fitting within the definition outlined above.

Summary of the search protocol

Academic papers were searched for in Scopus only. Only papers published after 2000 were included in the search, with the view that the key types of batteries in focus are those that are large electrochemical storage technologies, as per Batteries Europe scope. Four searches were conducted, and the results first checked for scope, and then de-deduplicated. In each search, 'battery' was a key term searched for in the title, abstracts or keywords of records. Scopus automatically includes plural variants (e.g. 'batteries') in such searches.

The identification of SSH papers used 3 separate techniques (use of search terms, Scopus 'Subject area' classifications) and journal titles identified as SSH oriented over 4 searches:

1. Use the Scopus 'Subject Areas' classification, and **limit to** social science areas
2. Same as 1, but **exclude** subject areas not defined as social science
3. Augment the basic search to "battery AND (society OR social OR human OR people)"
4. Limit the search to within 19 social science-oriented journals

Exclusion criteria

Returns from all the above were scoped manually for inclusion. Key criteria for exclusion were:

- Not about batteries in any way. Battery is a synonym used in psychology, law and the military

Inclusion criteria

To be included in the final count, all those not excluded by the process above, where then subject to a second sift to identify paper that were:

- Clearly approaching the subject with a recognisable SSH perspective, broadly defined
- Where batteries were a significant or central part of the paper, not just a background concept

Across the 4 searches set out above, an initial 1599 records were deemed in scope following the application of the exclusion criterion. Following application of the inclusion criteria above, 153 records were deemed SSH research on batteries. It is worth noting that this is clearly a relatively small corpus on what is otherwise a relatively large field of research. For context, a basic search for batteries as above (in titles, abstracts and keywords), limited to keyword "lithium-ion batteries", around 86,000 records are identified. Within this, if the subject areas are limited to SSH, around 1800 records are identified, around 2% of that literature. Once a more manual search is applied, only around 10% of those 1800 are within the scope, representing around 0.2% of the initial 86,000.

Mapping the returns

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Using the titles, abstracts and sometimes journal titles, an attempt was made to map them against social science disciplines. Ideally it would be good to be able to map them against the full typology set out above, but in practice it is not so simple. Instead, it was easier to identify general sub-categories of SSH disciplinary focus of the paper across 6 categories, including one that is more method than discipline – modelling. It made sense to label these separately in part because it was often difficult to attribute such studies to particular disciplines, but also because they are so common in the corpus. Papers were multiple-coded so each record could be marked both political science and economics, for instance. No weighting was added to these.

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676

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Position paper

Hybridisation Task Force

April 2024

In cooperation with

BEPA Batteries European Partnership Association

ACKNOWLEDGEMENT

Batteries Europe Secretariat is an EU-funded project that has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676.

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The current publication constitutes a short and preliminary version of the position paper. The final and more extensive version will be published in Q4 of 2024.

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Acknowledgements: We would like to thank Spyridon Pantelis (EERA) for the overall coordination of the Task Forces, Alessandro Romanello (EIT InnoEnergy) as coordinator of Batteries Europe, and the BEPA Secretariat for their support in the operation of the Task Force. Special thanks to Fatima Ahmed, Adeola Adeoti, Lucia Sardone (CLERENS), and Maria Luisa Fernandez Vanoni (EERA) for editorial support. We would also like to acknowledge the inputs and considerations from the European Commission, the Batteries Europe Secretariat and Batteries Europe Advisory Board.

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This project has received funding from the European Union's Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

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ABBREVIATIONS AND ACRONYMS

Abbreviation	Definition
AC	Alternating Current
BE	Batteries Europe
BEPA	Batteries European Partnership Association
BESS	Battery Energy Storage System
BMS	Battery Management System
CAPEX	Capital Expenditure
DC	Direct Current
EMS	Energy Management System
ESS	Energy Storage Systems
ETIP	European Technology and Innovation Platform
EV	Electric Vehicle
HESS	Hybridisation of Energy Storage Solutions
HVDC	High voltage direct current
ICE	Internal Combustion Engines
kHz	Kilohertz
LFP	Lithium ferrophosphate
LIBs	Lithium-ion batteries
LiCoO2	Lithium cobalt oxide
LTO	Lithium titanium oxide
MW	Megawatts
MWh	megawatt hour
NAS	High Temperature Sulphur Batteries
NCA	Lithium nickel cobalt aluminum oxide
NMC	Lithium nickel manganese cobalt oxide
OEM	Original Equipment Manufacturer
OPEX	OPerational EXpenditure
PCS	Power Conversion System
PEM	Proton-exchange membrane
RES	Renewable Energy Systems
RFB	Redox flow batteries
RUL	Remaining Useful Life
SAF	Sustainable Aviation Fuels
SIBs	Sodium-ion batteries
SoC	System on Chip
SoH	State of Health
SRIA	Strategic Research and Innovation Agenda
TCO	Total cost of ownership
UPS	Uninterruptible Power Supplies
V2G	Vehicle-to-grid
V2H	Vehicle-to-Home
WG	Working Group

This project has received funding from the European Union's Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

1 INTRODUCTION

The REPowerEU plan[1] put forward by the European Commission in 2022 includes a considerable acceleration in the roll-out of renewable energy which in turn will put a greater demand on stationary storage solutions. Batteries offer excellent efficiency and from this point of view are a key asset to the development of the energy grid. However, in cases when consider a holistic stationary storage system that can offer both short- and long-term storage it may be worth considering a hybridised system.

In the EU Commission's Recommendations on Energy Storage 2023,[2] it is proposed member states continue to invest in research and innovation on energy storage, specifically on topics like long-term storage, hybrid storage solutions, behind the meter solutions for customers and the utilisation of electricity stored in electric vehicles batteries for grid purposes, i.e. Vehicle to Grid (V2G). Batteries Europe has on its part, initiated the development of a Task Force with a focus on Hybridisation of energy storage systems for both stationary storage and transport applications. This group is also following up on some areas that fall in between the topics of the Working Groups and Task Forces which are relevant to the battery research community, such as the V2G concept.

Traditional hybridisation can be defined as the bringing together of two unique systems to result in a beneficial situation for the energy storage requirements case. As a task force with the viewpoint of Batteries Europe, we aim to suggest what improvements are needed to enable hybridised systems through the mindset of battery research. This can be based on the performance, cost level, reliability or safety of the battery itself or indeed can be on the research needed for advancements in the battery or energy management system to facilitate optimal use in the selected hybridised application.

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1.1 Why can Hybridisation of energy storage provide an important solution?

Hybridisation can take the advantages that each system has to offer and combine these together to create a unique solution which may have greater reliability, durability and flexibility or better sustainability and in some cases arrive at lower costs. However, traditional hybridisation also comes with a greater initial investment cost of connecting the two solutions physically and this too can bring added complexity. In order to take advantage of the hybridised system, a good analysis of the balance of plant calculation is required for the specific case before installation. While it is not in the remit of this publication to investigate or determine the balance of plant, it is an important aspect to consider when implementing a hybridised system. In section 2 of this document, we take a deeper look at our definition of hybridisation, while in section 3 we provide a very brief description of technologies most commonly used in hybridised systems, to enable readers not familiar with such technologies.

In section 4, we firstly address some of the research needs which are common to all areas of hybridisation including development of power electronics, sensors and communications for HESS, software tools and digital twins, and the need to develop a network to ensure lessons are learned from earlier projects.

Following this, in section 5, 6 and 7 we address specific cases where hybridisation can be used in stationary storage, transport applications and within the charging infrastructure. While this is not a complete overview of the research needs for the hybridisation sector, it should provide the reader with an understanding of the scope of topics which need to be addressed.

In addition, section 8 addresses the policy aspects within Europe that are important to consider as these have a large impact on driving the business case towards using the optimal hybridised energy storage solutions with regards to Environmental, Governance and Societal concerns. This is particularly relevant in the case of stationary energy storge solutions and the ownership and operations of the energy storage assets. In addition, the development of standards for charging and refuelling both hybrid and non-hybridised solutions for road, heavy duty transport, waterborne and aviation will be essential to facilitate the growth of the industry as a whole. Without standardised solutions large scale roll out will not be possible.

In the appendix can be found an overview of some of the many projects the task for contributors have been involved in are highlighted. This aims to provide an understanding of what areas have been investigated and what remains to be done.

This position paper is aimed to provide a brief overview of some selected research areas and to address policy changes required in order to prepare the ground for large scale implementation of hybrid energy storage systems to support both the energy and transport sectors. These suggestions are considered with the European Commission and Member States representatives, policymakers, industry & start-up companies (including energy companies, maritime and aviation companies), the research community and associations & communities in mind with the goal to assess and propose key strategic research areas. The information herein may be used to support decisions regarding research to be carried out within future programs such as the European Commission's framework programs, EIC program, national and regional research programs etc. Of equal importance it is hoped to be a starting point for discussion concerning policy regarding hybridised energy storage.

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1.2 What are the thematic boundaries of this Task Force?

The task force on Hybridisation of energy storage solutions (HESS) is new within Batteries Europe and was established in autumn 2023. It facilitates the collaboration of experts from several sectors including stationary storage, aviation and waterborne technology who have worked with battery technology. While there are a lot of hybridised energy storage solutions which can be investigated our focus in this publication will be on hybridised technology combined with battery-based solutions. Herein is an initial view identifying topics which require research to enable wide scale implementation of HESS. However, prior to wide scale publication an extensive consultation process on KPIs is necessary with the WG5 (Implementation of batteries in transport sector) and WG6 (Implementation of batteries in stationary storage sector) and with stakeholders beyond Batteries Europe.

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2 DEFINING HYBRIDISATION

2.1 Traditional hybridisation

In this situation two or more unique energy storage systems are combined to provide a benefit to the chosen application. The benefit can include either one or a combination of the following: lower costs, improved performance, extended lifetime, improved reliability, greater sustainability and reduced emissions.

This can also be referred to as "hybridisation on the system level". While each of the unique energy storage systems has its own unit management system (such as a BMS), these need to be connected and combined to facilitate the use of both systems conjointly. The conjoined energy system control is referred to as the Energy Management System (EMS) through this document. An EMS is essential and is a digitally driven solution with converters.

Heterogeneous battery system – This is a specific type of traditional "external" hybridisation in which a system that uses two different types of batteries to provide different functionality to a single energy system. Several examples can be found in the maritime sector where one type of battery supplies power and the other supplies energy to a vessel. Another example is the case of stationary storage island in which grid flow (Li-ion battery system and Lead acid battery) energy and back up.

Micro-hybridisation is a term used in some industries such as aviation. This describes the situation where functions which have lower energy demands are provided for by a smaller energy storage form such as batteries, while the main energy system such as the engine is run on a different technology. For example, an aircraft may have its propulsion run on Sustainable Aviation fuel (SAF), however all or part of the auxiliary systems such as air-conditioning, landing gear control etc. may be run on batteries.

2.2 "Internal hybridisation"

This is a system that truly hybridises two or more concepts in a single system. A few examples exist which are composed of either a chemically or physically combination of two or more systems resulting in an entirely new technology which we will refer to as Internal hybrids. Examples of internal hybrids include, Powercaps which are a cross between batteries and supercapacitors and the Battrolyser which is a cross between a fuel cell and battery. In this position paper we have not covered internal hybridised systems.

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3 STATE OF ART TECHNOLOGIES DEFINITIONS

Herein we provide an overview of the most commonly used energy storage systems which are combined as a part of HESS. There are several means of energy storage, including electrical, chemical, thermal and mechanical some of which are not mentioned herein. These include Nickel based batteries (electrochemical), Carnot batteries (thermal), flywheels and compressed air (mechanical).

3.1 Electrochemical storage devices

3.1.1 Supercapacitors

Supercapacitors, also known as ultracapacitors, store electrical energy through the physical separation of charge within an electrolyte solution using high-surface-area electrodes to achieve high capacitance. The electrodes are typically made from activated carbon or other porous materials with high surface areas, allowing for efficient adsorption of ions. Supercapacitors have high power densities from 1,000 even up to 20,000 watts per kilogram (W/kg) and fast charge-discharge rates but low energy density, typically a maximum of 10 (Wh/kg).

3.1.2 Li ion batteries

Li ion batteries refer to a family of Li ion-based battery chemistries and typically have energy density ranging between 150 to 300 (Wh/kg). In general, most variations are seen in the cathode material and electrolyte used, which result typically in the battery having different characteristics mostly based on the cost and performance. These various battery chemistries are described in the roadmaps of Batteries Europe.

High power Li-ion batteries – Li-ion batteries can specifically be designed to provide high power with power density of for example up to 10,000 (Wh/kg) however this comes with a significant trade off on the energy density of the battery. The use of anodes with lithium titanate (LTO) or incorporation of silicon in graphite anodes along with the use of cathode materials consisting of lithium iron phosphate (LFP) or lithium nickel cobalt aluminum oxide (NCA) are commonly used for high-power applications.

High energy Li-ion batteries – Likewise Li-ion batteries can be designed specifically to provide high energy but in turn the power density may be sacrificed. Theses typically employ Lithium cobalt oxide ($LiCoO2$) or Lithium nickel manganese cobalt oxide (NMC) as cathode material and can provide an energy density even up to even 300 (Wh/kg.)

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3.1.3 Sodium-ion batteries

Sodium-ion batteries (SIBs) are a type of rechargeable battery that utilizes sodium ions (Na^+) as the charge carriers and typically has an energy density which ranges from between 100 to 150 watt-hours per kilogram (Wh/kg). Similar to lithium-ion batteries (LIBs), they consist of cathodes, anodes, and electrolytes. However, in SIBs, sodium ions shuttle between the cathode and anode during charge and discharge cycles, rather than lithium ions.

3.1.4 High temperature batteries

High temperature batteries operate within a temperature window from 120C up to 350C and can offer both high energy density with high power density. However, due to the elevated temperature of operation they are generally most suited for stationary storage applications. Zebra batteries based on Sodium-Nickel Chloride are one such example and operate with a liquid sodium negative electrode separated from the positive electrode by a B-alumina solid electrolyte. Sodium-sulphur is another example which operates between 300C-350C. While such batteries exhibit many advantages their main drawback is the requirement to continuously operate as if they become cold the electrodes will no longer operate.

3.1.5 Redox flow batteries

Unlike cell-based systems, the electrochemical conversion in redox flow batteries (RFB) happens in a continuous electrochemical reactor. This means, that the energy storage medium is fed as a fluid to the cell and after conversion the fluids are collected in a reservoir/ tank. The fluid is regenerated upon charging of the system. In a typical technical RFB, a two-tank design is used. The electrolytes are pumped in two electrolyte circuits, one for the minus-pole reaction (negolyte) and one for the plus-pole reaction (posilyte). The cells in a technical system are usually arranged in stacks, in a design like the one of a fuel cell system. The main advantage of a flow battery are the individual scalability of energy (electrolyte volume) and power (electrode area/ number of cells in a stack), as well as high storage efficiency and service life. Most applied technology is the all-vanadium redox flow battery, which utilise acidic vanadium sulphate solutions as energy storage medium (23Wh/L). Typical energy density of electrolytes is between 10 to 30 Wh/L., with some batteries like Zinc Bromine RFB can go up to 80Wh/L. Available installations range from 2 to 100,000 kW [3].

3.1.6 Lead acid batteries

Lead-acid batteries are a type of rechargeable battery that utilises a chemical reaction between lead dioxide (PbO_2) and metallic lead (Pb) in an aqueous sulfuric acid (H_2SO_4) electrolyte to generate electrical energy, typically with an energy density of 30-40 Wh/kg. They have been traditionally used in automotive applications (e.g., SLI = starting, lighting, and ignition), backup power systems, uninterruptible power supplies (UPS), and stationary energy storage applications. Sealed lead-acid batteries or valve regulation lead acid batteries utilise gel electrolyte. These batteries are generally

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maintenance free and safe however they are more expensive that tradition lead acid batteries are also require a specific charging profile to prevent overcharging.

3.2 Chemical storage devices

3.2.1 Hydrogen storage using Fuel cells

Fuel cells utilise hydrogen to produce electricity and can be used in a wide variety of applications. Unlike batteries, they do not discharge, but produce power for as long as hydrogen (or liquid ammonia) fuel is available. They are more efficient than standard internal combustion engines (ICE) but are considerably less efficient than batteries. Fuel Cells are considered useful for providing the baseload, however they do not withstand sudden changes in the energy demand which causes considerable degradation to the fuel cell system in particular to the membrane.

3.3 Thermal storage devices

3.3.1 Thermal storage using Heat pumps

Heat pumps are energy efficient devices that transfer heat from one site to another. By using a small amount of energy, they can either act as heating or cooling systems depending on the needs of the user. There are three types of heat pumps, based on where they draw the heat from: air-source heat pumps, ground-source heat pumps (geothermal) and water-source heat pumps. Heat pumps have become more and more popular in the past years and are widely used in residential, commercial and industrial settings for their ability to maintain comfortable indoor temperatures and for their low environmental impact.

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4 RESEARCH TOPIC COMMON TO HYBRID ENERGY STORAGE SYSTEMS

4.1 Efficiency and flexibility of power electronics

Power converters are a key component for operating electrical energy storage systems. For hybrid battery systems Power Conversion System (PCS) solutions are currently not optimised and standard inverters are used for each battery type, these inverters are then coupled at their AC side. Novel PCS solutions are necessary to reduce costs and provide modularity, flexibility and resilience to the hybrid BESS.

The optimal battery combination (Heterogeneous battery system) in a given hybrid BESS may include batteries with different voltage levels and peak power capability which adds a layer of complexity in the definition of these novel PCS, in particular if the intention is to avoid oversizing the PCS. Some potential solutions are explored at research level and need to be further developed to reach market applications. Some of these PCS can bring novelty at architecture, topology or control levels, examples of novel PCS are:

- ***Multiport power converters***: Ideal for modular solutions, can incorporate several battery systems with reduced cost. Battery voltage must be within a given range but are very flexible in the power management side.
- ***Multi-level power converters:*** Very flexible in terms of battery voltage range but extension of lifetime using multiple electrochemical systems with power electric systems optimised for extension of lifetime adds complexity to the control. Some limitations are encountered in terms of power management flexibility.
- ***Fault tolerant power converters***: Can increase costs slightly but ensure that the battery remains in operation when the converter has an internal failure.

Research needs:

- Optimisation and Demonstration of Power Converters with multiple electrochemical power systems which provide different voltage levels, peak power capacity and within different safety margins.
- Development of power control software for use on multiple hybridised units.

4.2 Hardware for Communication and Sensing for Energy Management System

Sensors can provide a host of information about the state of health (SoH) of energy storage systems such as batteries and fuel cells. These sensors need to be integrated in the energy storage system such as the battery and the information must be collected in real time. The correlation of this information

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for both components in a HESS can provide an overview of the overall SoH and provide the potential to calculation of optimal usage in order to promote longevity of the HESS.

There are activities and projects that have been suggested and followed by Battery 2030+[4] and promoted by Batteries Europe, to develop sensors for battery systems and these can be taken with similar approached to fuel cells and other energy storage systems. The key here is to combine the information from both energy storage systems in the HESS, in real time, to calculate an overview of the SoH of the system and provide real time feedback to the optimal operation of the HESS.

Research needs:

- Development of new types of SoC/SoH sensors, especially SoH sensors to allow to quantify the boundary conditions of stable operations vs demanding operation.
- Development of new digital tools, which could replace classical sensors by machine learning/AI-techniques or genetic algorithms to allow the complex analysis of existing BMS data.
- New lifetime models, which helps to predict best-case operations.
- All the results of the first three points should help to develop control strategies for operation with minimum-wear for the combined storage solutions in the HESS or tools to define the optimum layout and dimensioning of both storage solutions.

4.3 Tools and Digital Twins for simulation of hybrid energy storage systems

Due to the complex interaction of two or more storage systems, digital twins and real-time modelling can help to model interactions of fast control demand or demanding load situations. If two or more storage solutions are combined on a common DC-intermittent circuit, it can be especially beneficial for the understanding of such systems, when the load operations of the system can be monitored on all time scales up to kHz range (below the time-constant of the 50Hz sinewave). This models then should allow to evaluate control strategies for short and ultrashort duration control like allowing momentary reserve, preventing inclined load situation or just fast frequency control. Other applications, where real-time modelling can be beneficial, are steep power ramps, high ripple currents in the DC circuit or monitoring of oscillations on non-grounded DC-circuits.

Complementary the damage of short-duration operation of a lot of batteries has not been investigated in detail, e.g., effects of ripple currents on RFB or steep load ramps on high temperature batteries.

A more detailed view on modelling of battery storage can be found in the position paper of the Task Force Digitalisation.

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Research needs:

- New real-life models of hybrid energy storage up to kHz time domain
- Investigations on effects of short current fanks or ripple currents on BESS
- The two beforementioned points should be used to investigate benefits of HESS operation regards to lifetime.

4.4 Software to address a hierarchical dynamic Energy Management System

DC-DC architectures for intermittent circuits are derived from various applications, each with its unique characteristics:

1. Battery-based DC architectures:

- Small-scale (<1kW): These include battery-based UPS solutions for small devices. They typically use lead-acid batteries or LIB and operate at voltages like 48V.
- Electric vehicles: LIB batteries are commonly used on a 200-360V DC circuit, with a trend towards higher voltages like 500-1000V for better fast-charging compatibility.
- Electrical circuits on large ships: These applications involve long floating DC cables, often combined with Nickel-based batteries.

2. Non-battery based DC architectures:

- Solar strings: These are often connected at 400V or sometimes 600V DC levels.
- Large-scale (1-8MW): Wind turbine architectures commonly utilize >1000V DC, usually floating, as the cables are kept short in the tower head.
- Super large-scale (several MW to GW): These are HGÜ connections of transmission grids.

These diverse architectures serve as blueprints for HESS developments. Wind turbine development, particularly for high voltage components above 1000V, has driven the innovation of new components. However, there is a gap for components in the range of 400V, 600V, or 800V. There is a high demand for switches and SF6-free arc protectors. The future holds the potential for affordable new components from electric vehicle development, which would also benefit DC-connected HESS development.

Research needs:

- For optimisation of HESS solutions, new components for DC, especially safe and SF6-free switches, fused or non-fused disconnectors/ contactors would be highly beneficial.
- Solid-state DC circuit breakers for fast and quick DC current and arc extinguishers.
- In addition, standardisation of DC-levels would help component manufacturers to allow a better variety of components.

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4.5 Business cases for hybrid energy storage solutions (HESS)

A sustainable business model is required for all hybrid energy storage systems (HESS) which are installed. Research is needed to investigate the value creation case that the energy storage may deliver to its owner and to fully understand the market, policy and regulatory boundaries. All three factors are evolving as more renewable energy sources are introduced into the energy systems. In addition, software which optimises projects to ensure an economically and sustainable business case will be necessary. For the case of stationary storage, the concept of stacking services for energy providers has the potential to lead to more profitable business models, however both policy and regulatory considerations will affect this business case. Although business cases will have to be specifically developed for each case, collaborations between researchers, industry and regulators along with utilities will be necessary in the future to ensure both economic and sustainable driving forces work hand in hand.

Research needs:

- The development of software which optimises projects to ensure an economically and sustainable business case will be necessary.
- The development of business cases which considers both the positive and negative effect and profitability for stacking of services for all stakeholders involved.
- Examine the sustainability aspects of business cases involving hybridised energy storage solutions

4.6 Overview of research projects and results

There have been many national and European framework projects which either have been completed or are currently running concerning development, testing and demonstration of HESS, a taste of which is provided in the ANNEX 1. to this document. However, there is not a specific network or alliance focused on hybrid energy storage research within Europe and the results generated through projects are not correlated. Coordination of research activities can result in shared information concerning the HESS system and subsystem design informing sizing, technical performance, lifetime estimation and financial performance. With such a wide varied of data available from earlier and current research projects along with advancements in computation methods these results could be developed and utilised in a better way.

Due to the lack of assembly of project results, the lessons learned within project are often missed by researchers and industry stakeholders across Europe. A suggestion could be to extend a currently existing networks on energy systems to incorporate a group with focus on HESS. However it should be noted that there are areas which need hybridisation in the transport sector as well. An alternative could be to extend a current project on HESS which covers both the stationary storage and transport sectors to become a network beyond the lifetime of the project.

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Research needs:

- Support the development of a lasting network of researchers, industry, member states and EU commission which will collect and correlate data from past and existing projects to ensure sharing of the lessons learned. This community could also serve to provide guidelines for decisions of industry and policy makers developing the European energy and transport systems.

5 CASE STUDIES FOR AND IDENTIFICATION OF THE RESEARCH NEEDS FOR HYBRIDISED STATIONARY ENERGY STORAGE

5.1 Combining Long and Short duration storage solutions

The terms “long- and short-term energy storage” are highly dependent on the system requirements and application. In battery technology, long term storage capacity is currently considered to be above ca 12 hours with negligible decay of energy density. Redox flow batteries are considered for long-term energy storage. However, in regard to a pumped hydro power plant, long-term energy storage can refer to storing energy for several weeks or even months. The installation of long-term energy storage facilities is also highly dependent on the space, climate and landscape available.

Short-term energy storage demands can place a huge demand on any single energy storage system and may result in premature breakdown. This is the case with fuel cells which are found to experience significant ageing upon rapid peak energy demands, however they excel in providing a stable baseload. Both Li-ion batteries and Li-ion capacitors or supercapacitors are designed to handle sudden energy demands over a short period of time. Short term energy storage is needed for operations such as frequency regulation, voltage control and spinning reserves to name but a few.

Benefits of hybridisation can be experienced with a combinational of technologies with the benefit of extending the lifetime and improving the efficiency of the primary storage solution and in the long term potentially positively impacting on the overall cost of investment. Herein the expectation is that in tandem, the solution performs optimally but also with the added advantage of extending the lifetime and SoH of the primary storage scheme. Extending the lifetime of energy storage assets in the future renewable energy grids will result in huge economical advantage while making sure resource efficiency is also maximised, impacting sustainability positively. Furthermore, combination of high-power packs and high energy packs can mean that intensive power burst operational modes can be handled by the high-power packs (peak shaving etc) while the large energy demand being met by the high-energy density storage schemes. Such an operational segmentation can also result in reduced degradation and extension of lifetime of the overall storage system.

Potential hybridisation solutions examples:

- Redox flow battery in combination with Li-ion based BESS, hybrid of high-power storage and high-energy storage hybrids.
- Niche applications which apply pumped hydro with flow battery to increase life-time.

Research needs:

- Increase lifetime, the cycle life and the resilience of battery systems thus extending the life of the system.
- Significant decrease of cost of batteries specifically for hybrid stationary energy storage
- Investigation of lifetime thresholds and triggers for aging/degradation for the HESS and develop predication models for the individual components.
- Decrease the cost of the Energy management system for the HESS.
- Control systems with new DC architecture to determine the most efficient way to prioritise the use of the hybridised energy storage solution.
- Development of efficiency operations – with the support of digital twins, real time models of the HESS is necessary.
- Forecasting energy demand and supply using machine learning and artificial Intelligence.

5.2 Large scale and micro-grid assisted UPS solutions for critical infrastructure to provide resistance

Today's uninterrupted power supply (UPS) solutions are primarily designed to protect the control units of large centres, infrastructure or industrial processes such as data centres, telecommunications infrastructure and hospitals.

For larger UPS solutions, such as those used in hospitals, data centres and military facilities today diesel generator sets are used to protect these critical infrastructures. These generators are coupled with a switch that is activated when the main power supply is interrupted. The use of diesel generators, add to greenhouse gas emissions and they require regular maintenance. For smaller infrastructure, the energy storage of these solutions, range from 1 to 3 hours in duration, allowing for a controlled shutdown of processes during a power shortage. The main battery type used in these UPS systems are gel-type lead acid batteries, which have a long lifespan if kept under float charge. In the case of telecommunication stations, solutions typically utilise more expensive, 30 minutes duration, LIBs as backup power. In critical telecommunication infrastructure, such as radio communication for police or fire brigades, larger lead-acid based battery storages can be utilised.

While hybridisation of UPS solutions on small scale are not necessary, it may serve to improve the system on the larger scale if the costs of the HESS is lower than the cost of a single energy storage system.

In times of political uncertainty, it becomes important to secure not only critical infrastructure but also less critical but fundamental infrastructure on a broader scale. The emergence of renewable energy sources and stationary energy storage has made the supply and protection of infrastructure even more crucial. In this context, DC-connected grids with renewables and stationary storage can play a vital role.

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To operate such a DC-intersected grid, both short and long duration storage systems need to be integrated to meet power demands, including covering power spikes and providing energy for extended periods of operation. Possible BESS solutions could be RFB or high-temperature sodium batteries in combination with supercapacitors or high-power LIB. When combined with renewables, these secured micro-grids can offer a resilient grid scenario where a portion of the installed battery power is used to operate the infrastructure. This ensures prolonged independent operation without the need for refuelling, leading to a resilient and environmentally friendly infrastructure.

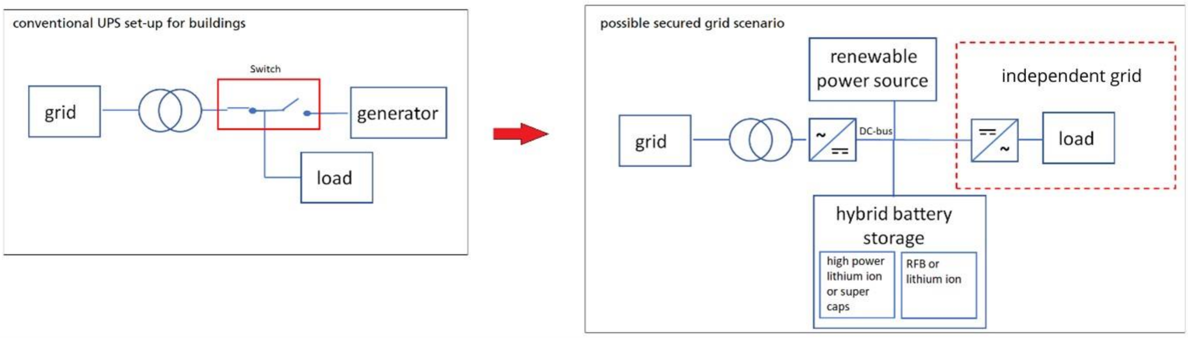

Figure 1: Schematic representation of conventional layout of UPS applications (left) and the concept of secured mini- or micro grids (right)

The business case for such UPS systems beyond small scale usage is unclear, due to market design factors, including the question of who is responsible for the maintenance and ownership of the service which is a "back up". It is expected that this may require legislative steps to enforce such systems.

Research needs:

- Optimal configuration of HESS relative to the needs of the UPS system.
- Increase reliability and flexibility of energy supply relative to the needs of the UPS system.
- Develop hardware components on multi megawatt scale specifically for HESS. This is currently available for wind turbines but is not considered for use with HESS up to MW level.
- Develop load management tools to maintain the baseload supply of critical infrastructure 24/7. This is also based on the system design of UPS "microgrid".

5.3 Hybrid energy storage solutions for energy islands

Energy storage technologies, coupled with advanced power electronics systems, are key to maintaining electrical system reliability when faced with increasing installation of renewable energy resources. Island grids are per definition, weak electrical systems, where stability issues are crucial in the pathway to integrate renewables. Two main challenges have to be addressed in the coming years:

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1. **Short term renewable instability** – Fluctuation of renewable generation create grid frequency and voltage fluctuations that are amplified in a weak grid as islands have, so technologies to provide fast primary regulation (range of ms) are fundamental to go ahead with a decarbonised energy system in islands.
2. **Long duration storage** – Due to the resource availability (wind and solar), in order systems to move big amounts of energy from days to weeks, are necessary to integrate a percentage of renewable energy higher than 60-70% (approx. numbers to be assessed case by case).

Hybrid storage system has the capability to solve both two main issues to integrate a large amount of renewable energy in European islands. As example, a flow battery hybridised with a LIB unit can provide both services in an optimised system, or a hydro pump plant coupled with a LIB to provide fast primary regulation to the island. In the meantime, while conventional generation is needed to support renewables integration, hybridisation schemes like a LIB unit coupled to a gas unit can join fast primary regulation capabilities of a battery, with long term demand support of a gas unit, reducing the need to operate the system with a big conventional power reserve, and generation unit dispatched at low eff point of operation.

Research needs:

- Development of advanced control systems to integrate different assets for fast primary regulation.
- Optimal design configurations to provide frequency primary regulation and long storage capabilities with high operational efficiency.
- Simulation environment and digital twin developments to improve islands renewable scenarios assessment (hybrid storage but also renewable generation simulation tools).
- Long duration storage with an incremental energy density to reduce land occupation (critical island issue).

5.4 Momentary reserve with RES

The energy market covers time-ranges from milliseconds to maximum a few days ahead in advance. Currently, there are no markets for the provision of power and energy for ultrashort or ultralong durations. In the past, there was no need for markets in these time domains as power control was achieved through spinning masses in power plants for short durations and a secure supply of fossil energy sources for longer durations. However, with the phasing out of fossil fuel-driven power plants, the growing demand for solutions, and the increasing intermittency of generation (from solar or wind parks), there is a need for solutions to address the resulting supply insecurity.

The absence of spinning masses, which play a crucial role in stabilising the grid in ultrashort durations, will impact power quality. Power quality is determined by synchronous sine waves of alternating current and balanced power in each of the three phases. The switching time of regular power

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electronics used in grid inverters operated by renewables or storage is typically too slow to meet the demand for ultra-fast power control. Therefore, the transition from regular power plants to power electronics-operated renewable energy sources will create a greater demand for fast power control. This demand will initially arise in larger islands or more isolated grids with a high penetration of renewables but could also become significant on the mainland as conventional solutions for baseload generation are phasing out.

Several solutions can meet this demand. For instance, researchers are exploring the utilisation of the inertia of wind turbines to generate virtual inertia in the grid. Another viable solution for ultrashort durations is the development of power electronics with fast-control capabilities, enabling power compensation within half a wave of a sine water (in the kHz range). This could enable renewable energy providers to function as fully-fledged power plants. However, to ensure the necessary power and continuous energy supply, a hybrid energy storage solution comprising both short and long duration storage is the most viable option, akin to a conventional power plant. The short-term storage component could potentially be supplied by ultrafast supercapacitors (referred to sometimes as ultracapacitors), but these must be part of a hybrid energy storage system.

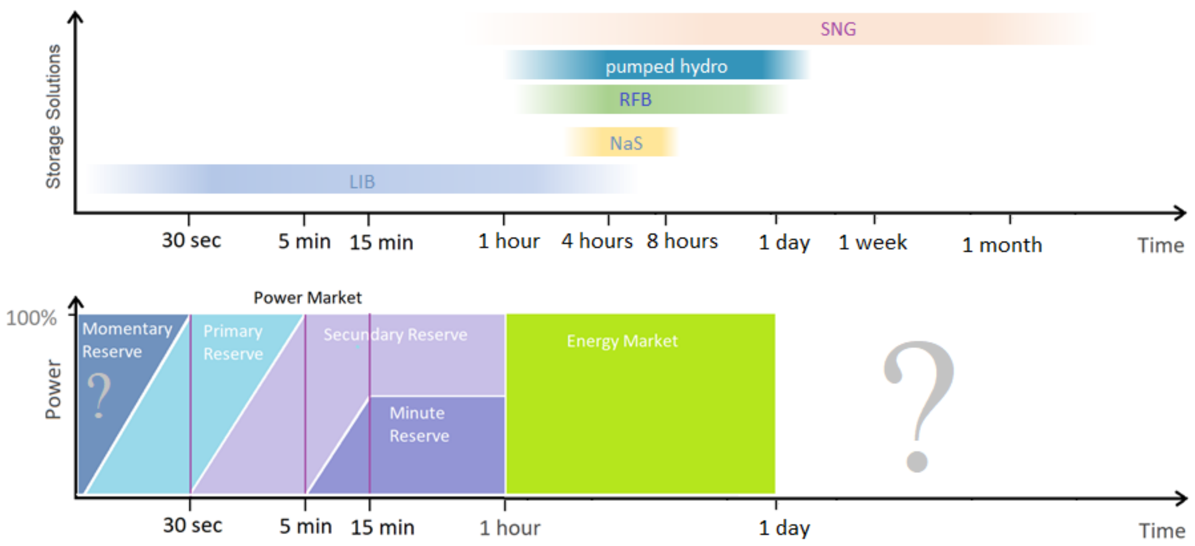

Figure 2: Scheme of a typical time dependant energy market in europe (could differ from country to country) as well as potential energy storage options (LIB = lithium-ion batteries, NAS = high temperature sulphur batteries, RFB = redox flow batteries, SNG = synt)

Business case: Currently the market design is unclear, however with increasing installation of renewable energy and the decreased use of fossil fuel energy, power quality will need to be addressed for larger islands in Europe which are not well connected to the central grid.

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Research needs:

- Development of fast- control of inverters in the range of several 10 - 100 kHz
- Scaling up the HESS with inverters to ensure quality of power.
- Combination of long- and short-term energy storage on multi-MW solutions to allow renewables to act like a power plant on the energy market.
- New business models for momentary reserve, grid-shaping, improvement of power quality.

5.5 Hybrid energy storage solutions for deferral of grid investments

Electricity grids in many parts of Europe (including the Netherlands) are reaching their capacity limits[5]. This is caused due to a mismatch between the demand and supply, especially in the High Voltage network. Expansion of power grids is both expensive and time-consuming and needs critical planning and hence solutions of energy storage that can augment or reinforce grid capacity is essential, especially in those cases where access to the High Voltage/Medium Voltage network is difficult or simply not possible. Thus, virtual power grids or microgrids with energy storage which can relieve the need for an augmented centralised power grid is needed. Hybridised energy storage schemes with provision for ancillary services while also meeting the local energy needs for the capacity augmentation can be key applications that such a virtual power plant can serve. Furthermore, accurate tracking of SoH of the hybrid storage scheme (as described above in section 4.2 -Hardware for Communication and Sensing for Energy Management System) can yield an extension of useful lifetime of the overall storage system, thereby saving huge capital investments in billions both at the power system capacity augmentation level but also in the hybrid BESS maintenance costs. HESS can thus be used as a mean to defer upgrading very costly and difficult to access infrastructure such as cables and converters while enabling ancillary services operations.

Research needs:

- Develop lower cost, reliable batteries with low or no dependence on critical raw materials.
- Prototype to demonstrate the hybridising of the energy storage system.
- Sizing and Demonstration of the feasibility of the proposed technology.
- Analysis of best placement of hybrid system in the energy system, identify critical points for potential installation.
- Consider use of 2nd life batteries in this a hybridised energy storage system.
- Linking projects which create hybrid energy storage demonstration to achieve best learning outcomes.

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5.6 Grid booster – CAPEX deferral phase

The installation of high-voltage transmission lines is a significant investment. To postpone the large-scale investment in costly transmission lines, battery storage installations could be employed. One widely discussed scenario is known as the "grid booster".

Typically, transmission lines operate below their full capacity to allow for the dissipation of energy over alternative lines during emergencies. In a grid booster concept, the safety margin of transmission is utilised to transfer more energy over the existing power lines, and instead utilise battery storage to be the safety margin in the transmission line. Therefore, the batteries in a grid booster offer an alternative safety mechanism. Large-scale battery installations are placed at central connection points along the transmission line to absorb excess energy during emergencies, while transmission lines operate at their maximum capacity. This concept can in principle also be added up with other services for the grid operator.

Tesla.Inc has built a 100MW project in Adelaide, Australia, and recently an installation of a 250MW grid booster in Kupferzell, Germany has started by Netze BW. Additionally, Fluence Energy Inc. and Tennet have announced a 100MW/100MWh project in Ottenhoven and Audorf Süd, Germany. It is worth noting that none of these projects currently incorporate HESSs. For example, the Kupferzell plant exclusively employs LFP batteries. However, the implementation of HESS could yield significant benefits for such applications. Combining long-duration Redox Flow Batteries with high-power LIBs combinations could provide both rapid response capabilities and high capacities, enabling longer utilisation of the grid-booster mechanism. Hybridisation can facilitate the storage of energy for a long duration (up to months) of time, LIBs are not highly efficient in this regard so the use of hybridisation in this case would be beneficial with regards the anticipated losses of energy and hence cost.

Research needs:

- Extend grid models to incorporate hybrid energy storage grid boosters to defer building of massive grid infrastructure with HVDC links.
- Demonstrate flow batteries along with Li ion batteries in a grid booster and study of costs.
- Develop a digital twin of the grid with HESS included.
- Develop business cases and policy both nationally and cross European boarders.

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5.7 Single-family homes (<50kWh/day) - Utilising batteries and heat storage options to achieve better efficiencies of battery systems

Usually long-duration storage systems have a lower efficiency than short-duration solutions. This means, that in these kinds of systems depending on the generation costs and lifetime, the OPEX costs can exceed the CAPEX costs[6]. If the application has also a heat demand like residential solutions, there can be an incentive to increase efficiency by hybridising the BESS with a heat storage solution. This is especially the case in residential energy storage solutions. In the past, a few of such HESS solutions have been built (see e.g., project BiFlow) to utilise the high heat capacity of a RFB storage in combination with a heating element and an additional heat storage to utilise waste heat of the RFB. Such combinations can also be extended to larger scale to allow district heating, e.g., with a community storage which distributes preheated water with low insulation demand to individual heat-pump and heat storage units. These concepts could bring new efficient solutions to the residential market.

Research needs:

- New hybrid battery solutions with integrated battery storage for residential applications, maybe in addition with heat pumps or geothermal storage or classical heat storage for increased energy efficiency. A special application could be e.g., long duration community storage with near-distribution heat grids and local heat pumps.

5.8 Vehicle to Home (V2H) and Vehicle to Grid (V2G)

This area of V2H and V2G is not strictly under the topic on hybridisation, however the experts of the Task Force Hybridisation feel it is important to raise awareness of this topic and use this opportunity to highlight its huge potential benefits to society as a whole.

Concerning V2G, it's easy to imagine thousands and tomorrow millions of vehicles feeding energy back into the grid during peak consumption hours (when workers return home in the evening), thereby limiting peak consumption. V2G is foreseen to be operated at low power because the impact on the battery aging is lower and the battery efficiency is better. With the aggregation of thousands of EV in a town or region can easily result in reaching high reinjection power. Charging of vehicles can then take place during the night when usage is generally low.

Despite the absence of technological barriers on bi-directional chargers in vehicles, V2H and V2G solutions are still very marginal in the world of electric vehicles. However, they could bring value to both vehicle owners and electricity grid operators.

Concerning V2H, being able to use the energy from its own vehicle at home, would make it possible to:

- replace the grid for short periods when the grid disappears.
    - use during the day cheaper energy charged at off-peak times during the night.

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* and potentially reduce the maximum power of its electricity contract, and therefore its cost.

The roll out of the V2H and/or V2G technology in Europe is hampered currently mostly due to policy. In addition, there is a lack of clarity concerning who has the responsibility for electrical management as this is bidirectional and requires bidirectional power electronics. It also requires a good deal of trust to enable this. There is a need for both policy and legislation change to create a flexible business model for V2H and/or V2G applications.

Research needs:

* Advancement and demonstration of bidirectional batteries in vehicles for use in V2H and V2G, not only at vehicle level but also at a fleet of vehicles level, to have significant impact on the grid.
* Improve the efficiency of bi-directionnal chargers especially at low power (around 2-3kW) .
* Technology, including new sensors to enable practical real time testing of State of Health (SoH) of battery.
* Analysis of the impact on SoH of battery systems over extended cycling

To see these solutions adapted on a large scale, it will be necessary to measure more precisely the impact of these additional charging/discharging cycles on battery ageing, and then evaluate and subsequently reward the contribution of the end-user to the grid.

5.9 Neighbourhood batteries / high power with high energy

Batteries when installed in a house result in unused capacity, with a battery cycling within a smaller thresholds of SoC. This results in a reduced capacity utilisation factor of the energy storage system and hence is an inefficient use of the resource. A more centralised approach within a neighbourhood or sub-regional level can mean better utilisation of the battery, also now considering battery playing a role in grid congestion and ancillary service provisioning apart from storage subscription to the individual houses. Further, a shift of storage scheme from the individual customer level to the sub-regional level would mean reduced costs for the customer while ensuring higher added value o the services offered.

A HESS (e.g.: LiB + Flow Batteries) can yield a total cost of ownership (TCO) reduction while enabling an interconnected and reconfigurable network of energy storage to aid the grid for both proper operability but also during contingencies. Furthermore, apart from a stationary neighbourhood battery, several mobile batteries of parked EVs can form an interconnected storage pool that can serve as a neighbourhood battery when upgraded with V2G possibilities. In such case, the mobile batteries present a case where, advanced BMS in combination with diagnostic and health assessments to

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manage energy, SoH and Remaining Useful Life (RUL) of the connected individual batteries becomes important.

Business case: Policy and ownership of battery is the main issue here. In addition, a good business case for both stationary batteries and mobile neighbourhood EVs-V2G needs to be developed.

Potential hybridisation solutions:

- RFB + Li-ion Batteries (High Power/High Energy) (Stationary Neighbourhood Batteries)
- Li-ion Batteries of varied chemistries for mobile neighbourhood batteries

Research needs:

- Advanced BMS and diagnostics for stationary and mobile battery-based neighbourhood batteries.
- V2G infrastructure and interconnected mobile EV batteries as stationary batteries – (neighbourhood EVs-V2G).
- Energy management and ancillary services provisioning in both stationary and mobile neighbourhood batteries.
- For EVs in the neighbourhood, several different EVs (brands, OEMs, capacity, chemistries etc.) with different battery packs, SOH, RUL, BMS etc. will all need to be integrated.
- Peak shaving with high power storage technology and energy storage with high energy storage for preventing over sizing and high-capacity utilisation.

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6 CASE STUDIES FOR HYBRIDISATION IN TRANSPORT

6.1 Waterborne

In Europe the maritime transport sector has been taking action and is continuously researching and implementing new technology to transition to zero-emission. One of the main leading bodies in this sector transition is the Waterborne partnership7 which identifies and, together with the European Commission and industry, funds much of the necessary research to achieve zero emission waterborne transport. This very transition is in turn complicated by the many policies, rules and regulations that govern the maritime shipping sector on several levels. Achieving zero-emission waterborne transport concerns approximately 55,000 merchant ships and around 12,000 inland vessels and has two aspects:8 while part of the existing operational fleet must undergo retrofitting, the remaining vessels will be replaced by new-builds. The latter will be required to become zero emission as soon as possible, by for example employing electric and/or battery drives and adapting their onboard fuel storage in a way that would ease the transition to hybrid power units.

One way to test and prove innovative technologies for maritime greening is retrofitting existing vessels which operate with relatively small power demands by for example, converting their propulsion systems to battery electric or fuel cells, as well as employing containerised energy storage for batteries. The need for retrofitting is quite critical considering the low turnover of the fleet and the large number of old operational vessels with low energy efficiency and large environmental impact, such as for inland waterway vessels. Another obvious target for retrofitting is cruise ships, which require high amounts of energy. Since they operate on an electric drive system, they will require electric energy storage and energy harvesting technology. For new-build cruise ships, hybrid energy systems such as fuel cells in combination with batteries and combustion engines are envisioned in addition to the above-mentioned energy harvesting and storage options.

Ferries are ideal candidates to become fully electric or employ fuel cells. However, for both new build and retrofitted ferries with a range of up to 200 nautical miles, the focus will also be on hybrid systems (a combination of ICE/electric drive, fuel cells, battery packs and renewable energy) allowing for full battery electric transit and zero emissions during approach and harbour stay. For ferries with ranges above 200 nautical miles, the most applicable solution remains ICE combined with alternative fuels.

For offshore vessels, which come in a large variety of sizes, the most applicable designs include full-electric and hydrogen-powered fuel cell solutions. Currently however, some of the new-build offshore vessels already operate on hybrid battery systems. One example is a hybrid design comprising hydrogen-powered PEM fuel cells combined with diesel ICE (p. 23 in SRIA report)[9].

From the point of view of the environmental impact on climate change stemming from the maritime sector, the main challenges are air pollution, water pollution and noise pollution (in particular underwater noise). Both the use of sustainable fuels and hybridisation (where electricity will be used as an auxiliary power source) contribute to attaining these three environmental objectives. In new builds, this means that the vessels will have an electrical drive which would allow a hybrid power design that includes batteries, fuel cells and ICE. The research priority medium-term is the development of ship systems capable of reaching overall efficiency of minimum 60% range by use of fuel cells alone or with hybrid systems.

One important operational objective within the hybridisation of the maritime shipping industry is related to port-based activity/port infrastructure[10] which is addressed in Section 6 below.

Research needs:

- Standardisation of the installation within a wide range of ships and of the integration within electrical grids (AC and DC).
- Standardisation of the charging connections between the vessel and the shore, both in ports and charging hubs.
- Improving the operational benefits of batteries while ensuring longer zero emission sailing.
- Upskill shipowners and operators in best decision making and operation.
- Optimal ESS sizing and hybridisation based on real operational load profiles and need for open-access data.
- Modular multi-MW heterogeneous battery systems, intelligent power electronics (with condition monitoring) for optimal operation.

6.2 Aviation – Hybridisation for light duty & heavy duty aircraft

Aviation is accountable for less than 5% of the global CO2 emissions[11]. Even though this may seem like a relatively low figure, the climate impact from aviation is significant in light of everything that we must decarbonise in order to reach net zero emissions by 2050. Decarbonising aviation is not an easy task; electric-hybridisation and electrification of aircrafts come with increased onboard weight, which in turn leads to the aircraft needing even more power to perform; this is the so-called 'snowball' effect[12], a term often used in the aviation context. That being said, it was already shown that implementing hybrid-electric aircraft technologies and phasing out fossil fuels in short-range aviation may lead to significant benefits to both human health and ecosystems' quality. As such, one of the key aspects towards zero and low emission technologies within aviation is research into novel hybrid-electric solutions (distributed/electric propulsion) and their incorporation into regional and short-range flights as was also highlighted in the 2021 SRIA from the Clean Aviation Partnership[13]. This will trigger the development of new and efficient designs for aircraft configuration, in particular when it comes to flight control and on-board energy concepts. Electric propulsion is a promising concept for optimised aircraft performance and reduced fuel consumption. The developments in the hybrid-electric technology will further be of use for commuter and vertical lift applications. Hybrid electric and dual-fuel concepts are considered, as well as concepts with hydrogen fuel-based propulsion coupled with advanced battery technology energy storage.

The first candidates in the aviation sector that will adopt hybrid-electric propulsion technology are aircrafts operating at distances of less than 500 km (regional connections) with a capacity of less than 100 seats. It is expected to have this concept ready for commercial application by 2035. Different

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hybrid systems are being tested, such as either a thermal engine coupled with electric configuration, or a fuel cell system coupled with electric configuration.

Several hybrid architectures are under investigation including hybrid-electric (parallel hybrid and series hybrid) and turbo-electric. In the hybrid-electric design, when the additional electric energy is not used for high power demand actions such as acceleration, it can be stored in batteries.

In the parallel hybrid-electric structure, the thrust is generated by a conventional thermal engine coupled with an electric engine in high power demand flight phases such as take-off.

In the series hybrid design, electric power is provided by a generator plugged into the main turbo engine and either stored in a battery when not in use or used to power electric motors and propellers.

In the turbo-electric design, the electricity generated by a turbo machine via a turbo shaft is used to drive multiple, distributed fans, driven by electric motors.

For larger regional aircraft it is envisaged to develop a system based on a hybrid turbo-propeller equipped with a reversible thermal engine and coupled with batteries or fuel cells for additional propulsion power during critical phases in flight.

All power during taxi and gate related activities will also come from batteries and fuel cells.

One of the main research challenges it to develop a power management system to ensure an optimum split of the power source according to the flight phase. The total on-board power for regional flights will range from 2 to 8 MW, depending on the size and degree of hybridisation. The electric configuration may include efficient hybrid turbo propellers, electrical foldable propellers, electrical power storage, and all the necessary systems needed to implement a power channel above 1MW/1kV.

With regards to larger aircraft which travel over longer distances, micro-hybridisation may be a method to reduce emissions and fuel consumption. This is where smaller batteries systems are used to assist the thermal propulsion engine with some of the system tasks on board. According to Airbus, micro-hybridisation could increase fuel efficiency and reduce the environmental impact from the aircraft industry by 1-6%, and even 10% in the case of helicopters.

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Research needs for the electrification/hybridisation of the aviation sector.

Specifically with relation to batteries:

- Development and manufacturing technology for light weight batteries systems and components to support Hybrid energy storage systems (HESS) in aviation.
- Developing the integration and adaptation technology of a modular hybrid power pack (energy cells, power cells, high charge/discharge cycle); designing batteries for peak power delivery, along with the possibility to enable a high discharge current.
- Developing batteries and/or fuel cells with the ability to deliver high power in a relatively short period of time.
- Developing batteries capable of withstanding sudden temperature and pressure fluctuations.
- Developing technology for in-flight battery swapping.

For aviation in general:

- Developing an efficient hybrid configuration to provide both electrical and mechanical power for propulsion for example a turbo-generator (thermal engine + electric generator(s)) or a hybrid turbo-propeller
- Achieving modularity and developing a hybrid system to adapt to changing propulsion power ranges and to interface with aircraft electrical systems.

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7 CASE STUDIES FOR HESS RELATED TO CHARGING INFRASTRUCTURE

7.1 Hybrid refuelling-recharging infrastructure and hubs

While the case of refuelling-recharging of hybrid energy storage systems may not be strictly classed as hybridisation in itself, it is an important factor to enable the success of hybridised energy storage systems in transport. Fast charging has been a topic of discussion and research for some time and it continues to be an essential issue for aviation and waterborne transport among others. However, when we consider hybrid energy storage systems several additional group questions arise, among them the most challenging topic of how to refuel-recharge multiple systems in parallel in a safe manner.

For all transport modes, but in particular aviation and shipping, one very important aspect of integrating HESS is redesigning the seaports and airports in such a way that different fuel types and new technologies are accommodated for concomitant storage, as well as refuelling/charging. Special attention needs to be granted towards the safety of all ground activities, but in particular where the area is limited and activity levels are high. Large initial investments will need to be made for supplying power generation and other fuels such as hydrogen liquefaction and storage. The new infrastructure for the shift to alternative propulsion will thus need to include upgraded grid connections and fuelling possibilities regardless of the fuel type (SAF or liquid hydrogen), in additional to the provision of local power distribution infrastructure.

Safe storage and handling of liquid hydrogen (which must be kept at temperatures below 240°C) will be challenging for both seaports and airports. Furthermore, consideration needs to be taken for safe onsite generation and storage of electricity in relative proximity to onsite storage and handling of flammable fuels.

In the case of maritime transport, an important addition to the current port infrastructure is the construction of the offshore recharging/refuelling hubs. This would allow hybrid ships to recharge and/or refill outside the main port thus reducing congestion and waiting times. One of the challengers here could be supplying sufficient energy to the energy hub offshore. The same considerations on storing electricity and flammable fuels close to each other are valid here.

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Research needs:

- Development of fast charging batteries and infrastructure essential to maritime and aviation
- Modelling of multiple refuelling - recharging systems in parallel with considerations for safe design of the system.
- Development and small-scale demonstration of physical infrastructure for multiple refuelling - recharging systems.
- Development of digital twins for safe refuelling – recharging in real time.
- Building a sound economic and financial business case for dual refuelling - recharging infrastructure and accessing who could operate and take on responsibility for the same.

7.1.1 Charging Infrastructure – The Electric Road

The electric road allows a vehicle to charge and drive at the same time over a short duration. It involves part of the road being providing wireless charging to the vehicle as it drives over it. This solution is very interesting especially for trucks which need a large amount of energy for their trips, involving large, heavy batteries and costly fast charge infrastructures. On section of roads without charging infrastructures (Electric Road), the vehicle will use its own battery. The first studies show than it could be possible, with this kind of solution, to divide by three the size of the integrated batteries. Of course, a lot of technical challenges need to be addressed: safety, electric contact, DC grid deployment, etc. The potential benefit of the electric road is that this static and dynamic charging infrastructure resulting in the battery in the truck being smaller (thus lighter weight).

Research needs:

- Optimisation of battery technologies enables higher C-rate without impacting on aging.

Potential hybridisation solutions add the research questions posed:

- What is the optimum, size, technology of the battery depending on electric road charging capabilities?
- How to manage, in real time, the energy coming from the road (DC grid) and from the battery, depending on the state of charge, charging grid capabilities, etc.

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8 POLICY IMPLICATIONS

In the past years, under the Green Deal[14], the European policy framework for storage has seen significant improvements. Indeed, the revised Electricity Market Design[15] and the Fit-for-55 Package[16] acknowledge the role of storage in the future decarbonised system and, if correctly implemented, they will fuel the demand for storage solutions while consolidating their business case and facilitating their roll-out. Examples of how these new legislative texts can directly or indirectly enable use cases for hybrid storage systems include:

- Electricity Regulation[17] for stationary storage (with provisions on national flexibility assessments, national flexibility targets, and the possibility for Member States to implement capacity payments for new non-fossil flexibility assets)
- Energy Efficiency Directive[18] for storage solutions in buildings
- Alternative Fuels Infrastructure Regulation[19] for recharging solutions, vehicle-to-home solutions, and vehicle-to-grid solutions (the text focuses mainly on cars, vans, and trucks, but it also promotes electricity supply at ports for ships and inland waterway vessels and electricity supply for stationary aircrafts)
- RefuelEU Regulation[20] for aviation and the FuelEU Regulation[21] for maritime transport.

Despite this supportive framework, important obstacles still need to be addressed to unlock the potential of hybridisation.

1. There is no legal definition of a hybrid energy storage system

In line with the principle of technological neutrality upheld by the European Union, the new policy framework is mainly application-driven, it promotes mobile and stationary storage systems without clear-cut signals in favour of certain technological choices. While this approach is justified to enable fair competition in the market, in particular to the benefit of innovative solutions, this means that hybridisation has yet to be recognised as a concept.

It should be noted that the legal definition of energy storage in European law[1] reflects this principle of technology neutrality and hence does not exclude hybridisation. Nonetheless, to make sure that hybrid storage systems can also benefit from the new policy framework mentioned above, a joint definition of hybrid storage systems accompanied by further guidance from the Commission would be welcome. It could for instance help Member States in their transposition of the new provisions of the Renewable Energy Directive regarding permitting for storage facilities.

[1] Article 2 (59) of the Electricity Directive: "'energy storage' means, in the electricity system, deferring the final use of electricity to a moment later than when it was generated, or the conversion of electrical energy into a form of energy which can be stored, the storing of such energy, and the subsequent reconversion of such energy into electrical energy or use as another energy carrier;"

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2. The regulatory framework remains very fragmented

The policy framework remains greatly fragmented, with Member States fostering different approaches. And, as the implementation of the revised Electricity Market Design and the Fit-for-55 Package leave a lot in the hands of the Member States, this fragmentation is unlikely to diminish.

Three areas should especially be addressed:

- **Ownership of stationary storage** assets is governed by the Electricity Regulation. Transmission and distribution system operators should not, in principle, own and operate storage facilities, but are granted a number of exemptions (which differ from one Member State to the other). This makes it especially difficult to develop business models for hybrid storage systems based on diversified activities.

- There is **little legal certainty** for new ownership models such as storage owned by local energy communities. Efforts to improve legibility for project promoters would be welcome.

- **Safety** (including fire safety) requirements are critical for hybridisation. Indeed, hybrid storage systems face specific challenges linked to technology (e.g. combining batteries and hydrogen storage) and to application (e.g. more stringent rules for waterborne transport). Simplification and standardisation of safety requirements will be instrumental for the successful roll-out of hybrid systems. In the short term, in view of supporting innovation, knowledge-building should be promoted.

3. The business case for energy storage solutions should be further consolidated

The European Union has acknowledged the role of storage in increasing the penetration of renewables, containing electricity prices, and maintaining security of supply. However, building compelling business models for storage projects remains quite challenging. Even more so for hybrid systems and long-duration energy storage systems. This is because storage assets must rely on revenues stacking i.e. combine revenues streams from different markets (wholesale markets, balancing markets and ancillary services markets, capacity markets). Further attention should be granted to this issue.

Besides the three obstacles highlighted above, it could be useful to address other open questions like:

- **Certification of "green" electricity** when stored in a hybrid system (here, the Delegated Act on the definition of renewable hydrogen[22] could be used as a benchmark as it covers storage in its criteria on temporal matching).
- **Standardisation** for vehicle-to-grid and vehicle-to-home solutions - here, the Alternative Fuels Infrastructure Regulation[23] provides for the development of technical specifications, notably on communication between vehicle and recharging point for the purpose of interactions with the electricity grid. Finally, policy-driven opportunities for hybridisation should also be explored, notably:
- **Production of e-fuels for the aviation and maritime** sectors, as well as hydrogen production for the decarbonisation of hard-to-abate industries, as it will rely on a steady supply of renewable electricity to run electrolysers.

- **Security and resilience of critical infrastructure** - hybrid storage systems could help secure the energy supply for critical assets in the event of natural disasters, health emergencies, or man-made threats.

Generally, deployment of hybrid storage solutions to phase-out fossil fuels and help reduce the cost of energy, in line with the ambition set out in the REPowerEU Plan[2].

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9 RECOMMENDATIONS AND CONCLUSIONS

The ongoing aim of the European Battery research community is to create lower cost, reliable, safe and sustainable batteries, however in order to gain the advantage of implementing these batteries in combination with other technologies corresponding actions are needed. In order to achieve the widespread, large-scale distribution of HESS the following actions are required:

- Develop diagnostic techniques for SoH, both hardware and software (see also the position paper of the Task Force Digitalisation) and specifically for HESS, develop methodologies to combine these SoH diagnostics for hybrid systems.
- Develop efficiently power electronics for control of HESS which will integrate within electrical grids, in both AC and/or DC.
- Development of business cases for HESS is key to avoid experiencing greater strain on grid due to increase on usage and increased renewables. In islands grid systems this will be more pronounced, and it will be the first place where we experience these issues.
- Support the development of a lasting network of researchers, industry, member states and EU commission which will collect and correlate data from past and existing projects to ensure sharing of the lessons learned. This community could also serve to provide guidelines for decisions of industry and policy makers developing the European energy and transport systems.

In addition to research, policy and legislation will be needed to drive **business cases** for the implementation of HESS in order to drive the future energy transition. This policy needs careful consideration which must be based on a sound scientific background which can be supported by the research community.

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This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676

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ANNEX A - LIST OF SELECTED PROJECTS

Overview of selected currently running hybridisation projects

Application Area	Project	Combined technologies	Expected end year
Waterborne	SEABAT Horizon xxxx call xx project	Combined battery technologies	2024
Automotive	HELIOS (H2020) High-pErformance moduLar battery packs for sustaInable urban electrOmobility Services	Two battery types (NMC+LTO)	2024
Stationary	HYBRIS (H2020)	Two battery types (AORFB+LTO)	2024
Stationary	SMHYLES (Horizion EU - Just started) Safe, sustainable and Modular HYbrid systems for Long-duration Energy storage and grid Services	Aqueous-based HESS (Vanadium RFB + Aqueous supercapacitor), Salt-based HESS (NaNiCl2 battery + Aqueous supercapacitor) and HESS (Supercapacitor + Vanadium RFB with storage extension)	2028
Stationary	ISTORMY (H2020-LC-BAT-9-2020 n°963527)	Interoperable, modular and Smart hybrid energy STORage systeM for stationarY applications	2023
Stationary + EV charging stations	HAVEN (Horizon EU - Just started) High-PerformAnce Hybrid Energy Storage System for multi-serVicE provisioNing		?2027-8?
Stationary	HYFLOW (H2020)	Vanadium RFB + Supercapacitor	2024
EV charging stations	HEROES (H2020)	Li-ion battery + Li-ion capacitor	2024
Stationary + EV charging stations	OMEI (German federal funds) Coordinator TZE	2nd life Li-ion battery + Organic RFB for charging infrastructure	2023
Stationary storage	BYFLOW (German federal funds)	Vanadium flow batteries & Heat storage & Li ion batteries for residential applications	2024
Automotive Sector	R&D Project Uncovers Innovative Win-Win Combinations of Lithium-Ion Batteries and Supercapacitors (skeletontech.com)	Flywheels and Batteries – for acceleration	2023
Stationary	Dualflow ERC project	RFB storage with catalytic discharging unit, providing hydrogen for other stationary applications	2024
Stationary	ALMAGRID (Spanish national funding)	Hybrid LNMO + Zn-Air + Vanadium RFB	2023
Waterbone	NEMOSHIP (HEU)	Two types of Li-Ion batteries: HP and HE	2026

Waterborne	AENEAS (HORIZON-CL5-2022-D5-01-02-GA-101095902)	innovAtive ENErgy storage systems onboArd vesselS : Hybrid systems combining Solid State Batteries and Supercapacitors	2026
Waterborne	The Dutch Research Council (NWO) Funded Project: Maritime Batteries	Ship storage system as a heterogenous combination of LFP Solid State Battery (in development) and a traditional chemistry: NMC	2026
Waterborne	The Dutch Research Council (NWO) Funded Project: SEANERGETIC	Ship system expanded energy storage devices lifetime via AI-empowered control (SEANERGETIC) Fuel cells + Battery Hybrid	2026

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CONCLUSION

The six position papers illuminate vital cross-cutting aspects applicable across the entire battery value chain. Progress in these areas demands enhanced collaboration among stakeholders and significant financial backing to address the emphasized R&I requirements effectively.

Highlighting the role of **education and skills** on the transition towards an electrified society, some describe them as the true critical raw material in the transition. In the coming years, efforts are needed to train more individuals with industry-specific skills along the battery value chain. By coordinating efforts among Member States and expanding existing programs, swift progress can be achieved. However, to ensure effectiveness and consistency across regions, coordination and support actions are essential that should continue beyond 2025.

Digital technologies are an important enabler to achieve the development of innovative new services in battery technology and they contribute to achieve multiple socio-economic benefits. Through different applications or use cases, **digitalisation** is leveraging technologies that can deliver significant measurable benefits, such as cost savings, increased revenues and setting up new business models. Indicatively, some applications include digital twins, artificial intelligence and machine learning, computer-aided design, data science, advanced modelling, 5G, blockchain or the battery passport.

Despite isolated public perception concerns, advancements in battery **safety** have established them as relatively safe products. As battery sizes and applications expand, there's a growing focus on safety improvements throughout their life cycle, spanning from handling, manufacturing, maintenance, to second life and disposal phases. Enhancing safety at any level of the value chain, such as the material or cell level, it will entail reduction in costs and effort at system and application levels.

The **hybridisation** of batteries with other energy storage systems have the potential to harnesses the distinct advantages of each technology, yielding solutions with enhanced reliability, durability, flexibility, and sustainability, often at reduced costs. As this field is still evolving, strategic EU policies and standardisation initiatives will have a large impact on driving business cases and offering unique solutions to various industries (e.g. energy grid, aviation, buildings etc.).

Sustainability requirements are integral to every stage of the battery value chain, necessitating consideration across social, economic, and environmental dimensions. Balancing competitiveness and **sustainability**, particularly in EU regulations, is crucial, and end-users play an important role on acknowledging sustainability elements in battery products. Sustainability emerges as a vital factor for industry success, requiring early integration into the value chain to facilitate the green energy transition.

This encompasses also social sustainability and the imperative to better understand the complex interplay between technology and society. Bridging the gap between technological progress and societal context necessitates integrating Social Sciences and Humanities (SSH) disciplines into battery technology R&I agendas. Hence, stakeholders, policymakers, and industry leaders must embrace a "human-centric paradigm" wherein SSH becomes integral, not peripheral, to technological advancement.

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