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.

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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

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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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.

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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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Research and Innovation Programme under Grant Agreement N. 101069676

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.

- 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.

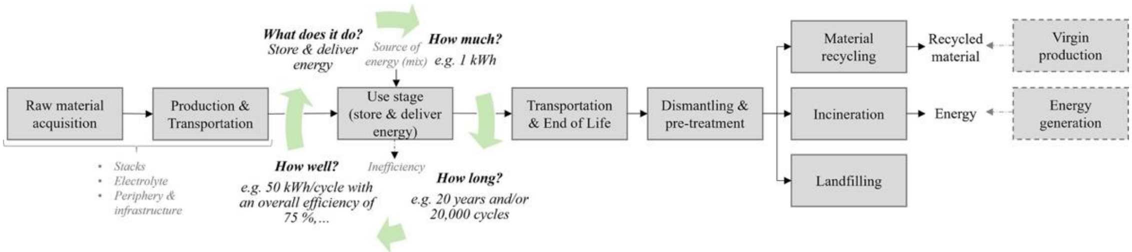

Figure 1: Suggested product system and functional unit definition for LCA of Flow Batteries. Taken from Dieterle M. et al., Life Cycle Assessment (LCA) for flow batteries: A review of methodological decisions. *Sustainable Energy Technologies and Assessments*, **53**, 102457 (2022) /doi.org/10.1016/j.seta.2022.102457.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

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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.

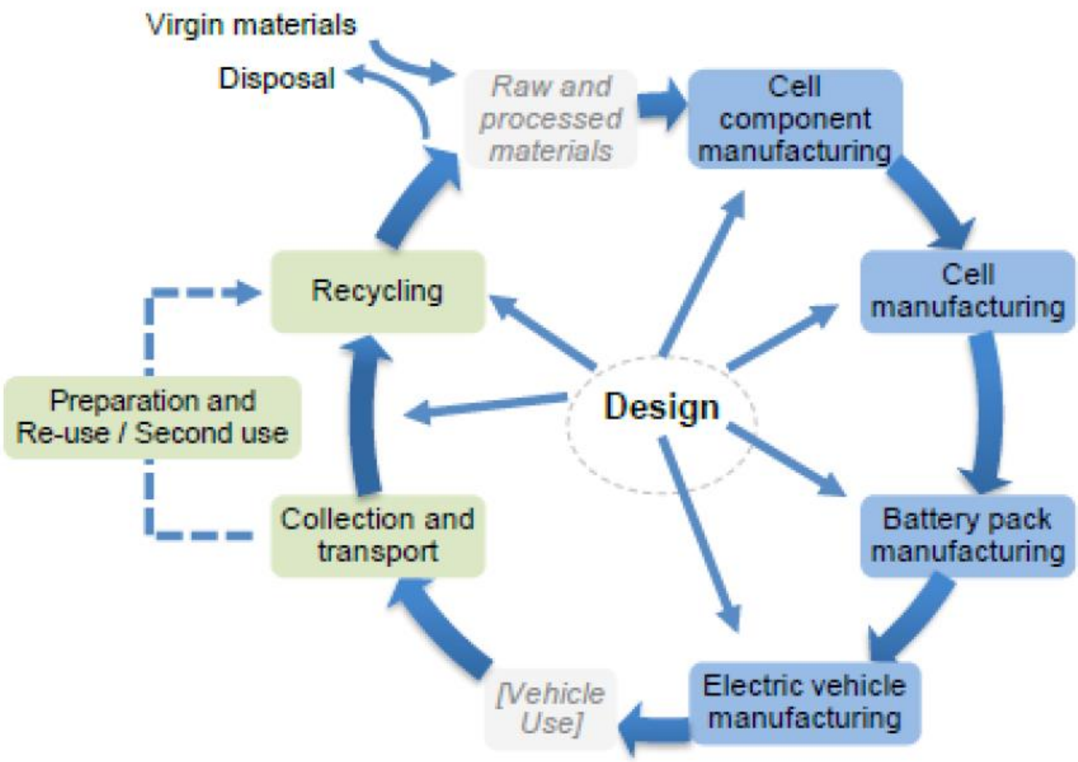

Figure 2: Circular view of the EV battery value chain for Europe. Taken from: Hill, N., Clarke, D., Blair, L. and Menadue, H., Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-10938-9,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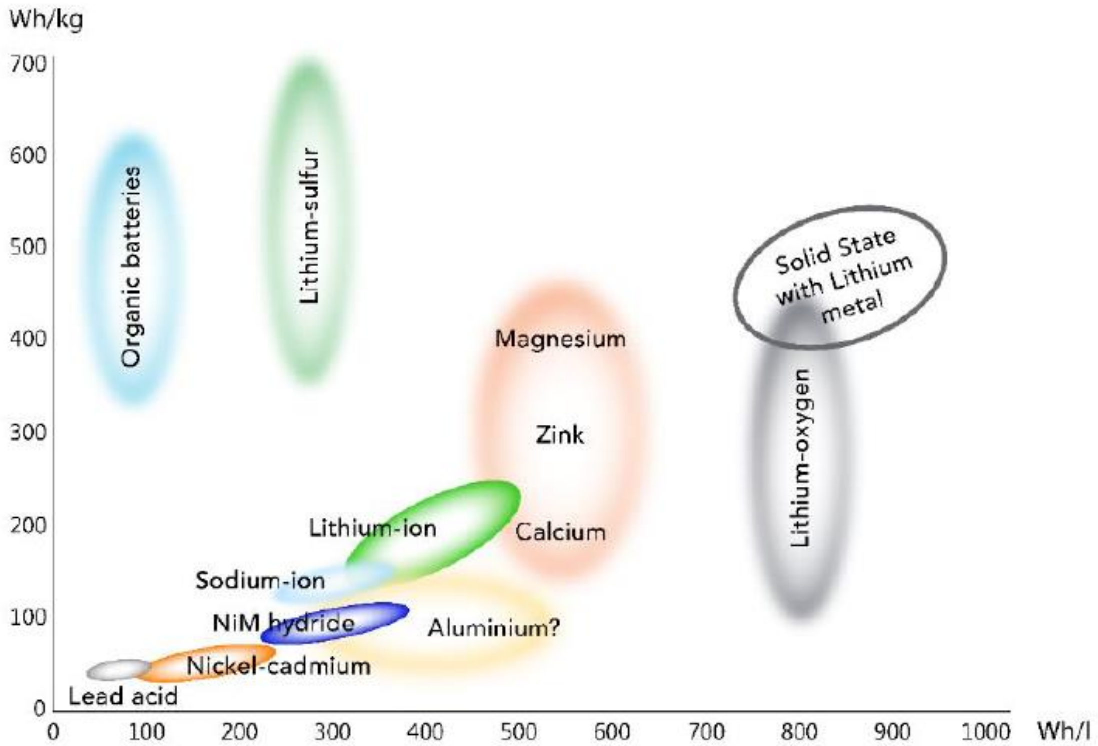

Figure 3: Overview of expected new battery chemistries. Taken from Battery 2030+ Roadmap (www.battery2030+.eu)

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.

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.

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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